MASTER OF SCIENCE BY RESEARCH

Stability modelling of micro aerial vehicles

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Award date:
2012

Awarding institution:
Coventry University

Stability Modelling of Micro Aerial Vehicles

By

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July 2012

Declaration

The work described in this report is the result of my own investigations. All sections of the text and results that have been obtained from other work are fully referenced. I understand that cheating and plagiarism constitute a breach of University Regulations and will be dealt with accordingly.

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Acknowledgments

I would like to thank my supervisors Michael Basini and Dr Humberto Medina for the motivation and guidance throughout the year. I would also like to thank the Aircraft Systems Development Officer Paul Fisher for all his knowledge and time that he has spent with me on the Merlin Flight simulator. I am especially grateful for my mum and dad for supporting me through University for another year, as well as my sister Jade for looking out for me. I would like to thank Alex and my friends for their entertainment and motivation that they have given me throughout the completion of my masters. “If only there were mini monkeys that could fly my tiny plane!”

Abstract

The design of Micro Aerial Vehicles (MAV's) is a growing field of study, with a broad range of applications. Research into the stability characteristics is still needed. Advances in this area could result in fully autonomous operations.

This project will cover the stability design phase for developing a fixed thin wing for an MAV. Preliminary results for the MAV wing design in a Computational Fluid Dynamics (CFD) simulation provides coefficient data and shows the development of tip vortices. From these results development in a flight simulator can be completed in this project to assess the flight dynamics of the design.

The project will give an overview of the design processes for an MAV developer to model and assess a design using flight simulation software and there capabilities for completing this task accurately. The simulation software uses the 'Coefficients' and 'Blade Element Theory' methods for modelling Flight Dynamics (FD). A significant contribution of this research includes the modelling of micro-scaled input variables and their corresponding output response for the assessment of the MAV's flight dynamics at low Reynolds number.

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Nomenclature

Re	=	Reynolds Number	[-]
v	=	Freestream Velocity	[m/s]
t	=	Time	[sec]
l	=	Characteristic Length	[-]
S	=	Wing Surface Area	[m]
c	=	Chord Length	[m]
b	=	Wing Span	[m]
L	=	Lift Force	[N]
D	=	Drag Force	[N]
Y	=	Side Force	[N]
M	=	Pitching Moment	[-]
N	=	Yaw Force	[N]
I	=	Roll Force	[N]
C_L	=	Lift Coefficient	[-]
C_{L0}	=	Lift Coefficient at zero AOA	[-]
$C_{L\propto}$	=	Lift Coefficient due to AOA	[1/rad]
C_D	=	Drag Coefficient	[-]
C_{D0}	=	Coefficient of Drag at zero AOA	[-]
$C_{D\alpha}$	=	Coefficient of Drag due to AOA	[1/rad]
C_{Dfus}	=	Coefficient of Drag on Fuselage	[-]
C_P	=	Coefficient of Profile Drag	[-]
C_{Din}	=	Coefficient of Induced Drag	[-]
C_{M0}	=	Coefficient of Pitching Moment at zero AOA	[-]
$C_{M\alpha}$	=	Coefficient of Pitching Moment due to AOA.	[1/rad]
e	=	Oswald Factor	[-]
E	=	Flight Endurance	[s]

Greek Symbols

μ	=	Dynamic Viscosity	
ρ	=	Air Density	
$\propto$	=	Angle of Attack	[deg]

Abbreviations

AoA	=	Angle of Attack	[-]
CFD	=	Computational Fluid Dynamics	[-]
CG	=	Centre of Gravity	[-]
FD	=	Flight Dynamics	[-]
FDM	=	Flight Dynamics Model	[-]
GUI	=	Graphical User Interface	[-]
LAR	=	Low Aspect Ratio	[-]
MAV	=	Micro Aerial Vehicle	[-]
PISO	=	Pressure Implicit with Splitting of Operators	[-]

I. Introduction

Stanford et al. defines an Micro Aerial Vehicle (MAV) as a class of unmanned aircraft, with a maximum size limit of 15cm, capable of speeds of 15m/s or less. Their intended goal is to be inexpensive, expendable surveillance vehicles. With the developments of micro electronics and communications it is now possible to create these vehicles (Grasmeyer and Keennon, 2001). This technological development is also rapidly increasing, causing the technology to become more economical and lightweight (Waszak and Jenkins, 2001).

Applications for MAV's have increased; initial uses were predominantly intended for defence and security purposes such as surveillance, chemical detection and tracking. Other commercial uses now being developed include rescue operations, traffic coverage and crop/wildlife monitoring (Cosynt and Vierendeeels, 2007). In 2007 it was published that the British Special Forces were using their own MAV's for reconnaissance in Afghanistan (Stanford, 2008).

These vehicles can have various configurations such as fixed-wing, flapping and rotating wings (Ifju et al, 2001). The MAV in this project will have a fixed-wing construction. Although it is based on a flexible membrane wing it will be modelled as a fixed wing. This design was based on the biological inspired bat wing.

MAV's should be stable however agile and be able to manoeuvre through complex terrain such as urban areas. An MAV operating in this environment may experience sudden wind gusts up to the same scale as the operating speed (Pelletier and Mueller, 2000). Sensing an oncoming gust, feedback control can be used to counter act the wind to maintain a controllable flight.

Personal computers now have the ability to simulate the complex behaviour of aircraft motion in real time. Commercial flight simulators have the ability to model Equations of Motion, Quaternion Transformation methods, Direct Cosine Euler Transformations and non-dimensional aerodynamic coefficients (Zyskowski, 2003).

This paper will look at modelling a thin fixed-wing MAV design in three flight simulation software platforms, to look at the capabilities of the software to model longitudinal stability.

The aim of this project is to find the best way to create a flight dynamic model for a preliminary MAV design and to visualise that model in a flight simulator for an MAV developer. It will start with just the dimensions and coefficients of a thin wing and should give the required Centre of Gravity (CG) for the location of the electronics for the propeller and motor. It will also assess the stability and if implement feedback loops is possible. Stability should also be assessed by means of wind gust effects due to the low flight speeds and the instabilities that wing gusts can cause. These should be performed in the vertical direction at controlled speeds and the simulator analysis should identify if this is possible. The approach used in this report should be clear to follow and easy to replicate so that the process can be used for the development of future MAV's.

II. Literature

This chapter will look into the relevant research needed to understand the MAV design and how it can be evolved and developed into flight simulators to increase productivity and future research development into MAV's.

A. Micro Air Vehicles

A Micro Air Vehicle (MAV) is a small unmanned aircraft system that is usually used for surveillance. The designs of MAV's are at the forefront of aeronautical research for a variety of different applications. Applications could include aerial reconnaissance, combat, search and rescue, logistics and even entertainment or toys. They could also carry payloads such as heat sensors for night-time surveillance or biological weapon sensors. Looking forward to future applications, surveillance requires prolonged amounts of time; the MAV may need to be able to work on low power or harvest energy from environmental sources such as sunlight, wind or manmade sources such as power lines.

The Black Widow MAV (Cosynt and Vierendeeels, 2007) is a perfect example of a developed design of a 6inch fixed wing aircraft designed as a feasibility study for military applications that took four years. It can carry out missions piloted by a video downlink weighing only 80grams. The aircraft took part in an endurance test showing that it could last 30minutes at a range and altitude of 1.8kt and 769ft respectively. With a fixed wing the aircraft will need to travel at a higher flight speed than a flapping wing design and would therefore cover larger distances. For this to happen a compromise has to be made on weight as higher powered motors and power will be needed. This design however could also take off and land vertically due to its design and weight positioning. From the feasibility study it was proved that propeller and motor efficiencies can reach 70% or higher which makes the MAV design viable. However significant instabilities occur as the small aircraft produces high frequency oscillations therefore a control system with a fast processor speed is needed and they are highly susceptible to wind gusts.

The Honeywell RQ-16A T–Hawk Unmanned Aerial Vehicle (UAV) (HighTech Edge, 2008) is an advanced surveillance and reconnaissance aircraft with two camera views that can hover and pinpoint targets. It does not have a fixed/flapping wing construction but a ducted fan design. It can reach airspeeds of 50 knots and a ceiling of 10500ft and weighing 8.4kg and being the size of military backpack, this application is the largest meeting high endurance needs. It is also the most complex aircraft as it is autonomous with the use of logging 100 waypoints. This application is currently being used in military applications. If this type of aircraft was scaled to a smaller size meeting all the needs of the application it would be a highly sort after device.

The Delfly Micro (Scientific Blogging, 2008) a flapping winged aircraft has also shown that it is possible for the MAV's can be produced smaller than 6inches. This aircraft has a wingspan of 4inches weighing only 3.07grams. This weight also includes its camera and transmitter, engine, receiver, actuators, airframe and the 30mAh lithium polymer battery. The endurance however is much smaller than the Black Widow with only 3 minutes of flight time and a range of 50 meters. Although the flapping wing design lacks endurance it is more manoeuvrable and needs more research done into the aerodynamic theories to be able to get the most out of this design. Stability testing on this design has not been documented however it is required to be flown indoors which shows that it will be even more susceptible to gusts than the black widow MAV and a control system could be used to improve the stability.

The Vapor is a fixed wing MAV (Parkzone, 2010) developed by Parkzone and sold as a toy costing £100. It can be flown indoors and at night due to the inbuilt neon lighting. This MAV aircraft weighs only 12grams with a wing span of 375mm .It carries a 3.7V Li-Po Battery, 3-channel 2.4GHz w/Spektrum DSM2 technology transmitter, custom designed gearbox and PKZ3302 Vapor Propeller with Spinner. It does not however have a camera or control system, due to its light weight design these could be implemented into a design but the fixed wing configuration may need changing to overcome the increased weight.

B. The Model

The initial starting point to this particular design was just an idea of a thin plate wing with a span of 0.1m with a mean wing chord of 0.0755m, with a 5% double camber configuration. A highly similar design was researched at Coventry University for an Undergraduate Degree and was found to be a very interesting characteristics and currently popular with MAV designs.

Table 1 MAV Model Wing Geometry

Geometry	
Wing Span	0.1 m
Wing Semi-Span	0.05 m
Root Chord	0.1 m
Tip Chord	0.02 m
Mean Aerodynamic Chord	0.0755 m
Taper Ratio	0.5 m
Aspect Ratio	1.33 m
Wing Area	0.00755 m^2
Wing Sweep	0 deg
Wing Dihedral	0 deg
Mass	10g

The cross-sectional dimensions that were used in this report can be noted in upon request, this information was used to collect data for a range of angles of attack (-180 to 180) needed for the relevant flight simulator models shown in this project. The reference point was be taken about the point x = 0, y = 0, z = 0.

In this design the original specified aerodynamic centre location (X= 43.578mm, Y= 0.068mm), was taken from the initial Computer Aided Design (CAD) design software OpenFoam. Initial geometry dimensions could then be calculated as seen in Table 1. This model was then used and imported into other software saved as a .STL file format to be used as image files for the relevant flight simulation software (Figure 1).

Figure 1 MAV Design in AC3D

It is assumed that this design is a solid but of any desired material and mass. This will then be reliant on the characteristics of the wing and the maximum allowable mass, these characteristics would be analysed using relevant software and verified. The rest of the design including propulsion system would be analysed and the desired to be chosen.

C. MAV Stability

Research has been done into the types of aerofoil configurations that are needed for MAV aircraft to fly at low speeds. Traditional aerofoil shapes experience low lift to drag ratios at these low Reynolds numbers. With thin wings the lift to drag ratio is greater to that of traditional aerofoil shapes but the figures are vastly smaller to those of a standard aircraft wing.

Schmitz (1970) was one of the first that found out through testing that a thin, cambered wing acted superior than a standard aerofoil when subjected to the low Reynolds number regime. It was then revisited by several researchers such as Laitone (2001) into showing that a circular arch with a 1% thick cambered wing produced the better results to that of rectangular profile results.

It has been shown that with increased camber there is an improvement in the aerodynamic characteristics over a flat plate (Pelletier and Mueller, 2000).

Lian et al. (2003) looked at a 15cm MAV membrane wing (figure 2) and modelled the stability of the design as a solid structure using CFD software running Pressure-Implicit with Splitting of Operators (PISO) method. The coefficient of lift seemed to increase from 0.5 to 2.25 from 0 to 50 degree angle of attack showing that the stall angle for this type of single camber of 7.5% is roughly 50 degrees (figure 3). It also stated that the model would not have the same characteristics to that of the original flexible membrane wing.

Figure 2 MAV with membrane wing(15 cm)

Figure 3 Lian et al. Steady and unsteady computations

Figure 4 Lian et al. Evolution of flow pattern for rigid wing versus angles of attack (from left to right, 6, 15, 27, and 51 degrees)

Lian et al. also modelled the vortices of the wing at Re = 5 $x10^4$ (figure 4). Wing tip vortices develop because high pressure air from beneath the wing meets with the lower pressure air from above the wing causing tubes of circulating air. These vortices can also occur at the edge of flight control surfaces. These vortices cause wake turbulence so reducing these is important if the MAV’s are to fly in formations or swarms as the turbulence may cause incontrollable flight.

Low aspect ratio wing geometries will endure higher induced drag to that of high aspect ratio wings. The wing tip vortex interactions seen with this type of small LAR wing cause the vortexes to become highly turbulent and may lead to roll instabilities. Winglets could be incorporated into the design to reduce this interaction. Winglets are designed to reduce the wing tip vortices they also add stability to the aircraft. They do this by reducing the severity of the induced drag. They also increase aircraft roll rates and lower approach and take-off speeds. The ideal sizing is dependent on the application and should include the following details;

- Cant Angle – required to reduce drag
- Twist Distribution – for uniform load distribution
- Sweepback – uniform aerodynamic loading across the winglet
- Taper ratio – maximize tip to maximise Reynolds number

(Masak 2008)

Figure 5 Pressure contours on rigid wing at different cross sections for a $\alpha = 6$ degrees with and without endplate, streamlines are also plotted: (a) without endplate; (b) with higher endplates.

Figure 5 shows the reduction in wing tip vortices by the use of an endplate which acts as winglet above and below the wing demonstrated by Lian et al.

Pelletier and Mueller (2000) also looked at cambered thin plate wings and varying low aspect ratios finding that it created better aerodynamic characteristics and performance with no hysteresis. However these experiments found that cambered wing of this type gave a large negative pitching moment coefficient, this moment can be compensated by adding a reflex camber. The use of reflex camber would be similar to that of a tail plane on an aircraft, used to balance the forces on the aircraft so that it is stable to fly. With a reflex camber the CG must be moved forward from that of the usual position. As the Bernoulli Effect shows that the reflex camber produces a downward moment this then creates additional drag.

Torres and Mueller (2001) also show that the Zimmerman and inverse Zimmerman acted better than elliptical and rectangular wings at low Reynolds number showing high lift to drag ratios. The Zimmerman shape is seen in this particular design for this project.

Low aspect ratio wings summon the expectations of short wide wings. A low aspect ratio would be 4:1 or lower. The aspect ratio can help predict the aerodynamic behaviour of the wing. Having a low aspect ratio directly affects the lift and drag as it has a smaller leading edge surface area for forces to act upon. There are three main reasons why you would choose to have a low aspect ratio wing for an aircraft;

- Structurally lower bending stresses will occur as well as less wing deflection.
- Manoeuvrability of an aircraft with low aspect ratio wings will encounter high roll rate and a high moment of inertia and therefore more manoeuvrable.
- It has a grater internal volume to house aircraft components.

Low aspect ratio wings produce less induced drag but much higher parasitic drag this is one negative that will result in high stall rates.

The journal paper covering the Aerodynamic Effects of Adaptive-Wing Micro Air Vehicles (Null and Shkarayev, 2005) tested designs that were highly similar to those that were being manipulated for this project (table 2). This similarity covered the chord length, camber and a similar wing profile (figure 6).

Table 2 Null and Shkarayev Wing Geometry

Camber	3%	6%	9%	12%
Wing area *S*, in.2	60	60	60	60
Chord length *c*, in.	8.125	8.125	8.125	8.125
Camber height *h*, in.	0.244	0.488	0.731	0.975
Thickness *t*, in.	0.02	0.02	0.02	0.02
Position of maximum reflex *d*, in.	7.312	7.062	7.000	6.937
Inverse camber *hi* , in.	0.094	0.187	0.250	0.375

Null and Shkarayev (2005) found that large positive, nose-up pitching moment coefficients were seen across all tested cambers at low Reynolds number. Noted in the experiment was that an increase in camber, increased the positive stalling value. It also showed that 3% camber gives the best lift to drag ratio but a wing with camber between 6% and 9% give the best low speed performance. This is due to the high lift to drag ratio and mild pitching moments near the stall angles of attack.

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Figure 6 Null and Shkarayev MAV wind-tunnel model and mount

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Figure 7 Null and Shkarayev 3% camber Re = 7.5x104

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Coefficient values derived from this testing can be used to compare values to that seen in this project to act as a comparison and reliability of results (figure 7 and 8).

By locating the CG (CG) far enough forward it is possible to obtain stability with a tailless aircraft. This however is only dependent on the aircraft having a positive (nose-up) pitching moment which is seen with the design in this project (equation 2.10).

$$C_{m_0} = sm\, C_L \quad (3.11)$$

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Figure 8 Null and Shkarayev 6% camber Re =$7.5\text{x}10^4$

By concentrating the lift forward of the aerofoils quarter chord point giving pressure gradients resulting in low $C_{L_{MAX}}$. The AeroVironment pathfinder is a tailless aircraft with high aspect ratio that uses the positive pitching moment to trim the aircraft. The deprivation in aerofoil performance due to positive pitching moment's, by changing wing sweep and twist these design floors can be overcome by moving the lift centroid to increase the span efficiency (Desktop Aeronautics, Inc 2007).

Waszak and Jenkins (2001) at the University of Florida analyse the stability and control properties of an MAV aero-elastic fixed wing with a wing span of 6 inches. The flexible membrane was chosen as it should deflect with unwanted wind gusts and is what is seen in nature. They tested in the basic aerodynamic research tunnel (BART) at the NASA Langley research centre to find out the best batten reinforcement design to that of a ridged design. The tested showed that the 1 batten design gave a better lift to drag ratio and increased the lift at higher angles of attack showing that the flexible membrane was better than that of a fixed shape. It also showed that there was a decrease in membrane deflection at higher angles of attack. Ideally this type of flexible membrane would be used to help with the stability of the aircraft.

Most MAV designs will act at low Reynolds number, typically between 10^4 - 10^5 due to its small size and low operational speeds. This may cause laminar separation bubbles caused by strong adverse pressure gradients resulting in loss of lift and increase in drag, in this case the reflex camber adds to the effect.

By shaping the aerofoil geometry so that transition occurs before the main pressure recovery region you can avoid separation by forcing a transition by artificial disturbances such as turbulators. These would be attached just before the laminar separation region to induce disturbances to cause transition to the turbulent state before it can occur.

- Mechanical Turbulator – They consist of added strips or bumps to the surface of the aerofoil. This device is less sensitive to change in angle of attack but causes larger additional drag. The height of the turbulators is dependent on Reynolds number and positioning. The lower the Reynolds number and further along the chord the larger the turbulator height. The mechanical turbulators would be ideal for this application as it is simple to enforce into the design.
- Pneumatic Turbulator – Consists of an array of holes in the surface of the aerofoil which ejects a small amount of air. The control of airflow can be controlled depending on the AOA.

Controlling the aircraft is usually done with a primary flying control unit such an aileron or elevator. With a tailless aircraft an elevon must be used this acts as the two units combined. By having elevons on a tailless aircraft the following problems arise;

- They decrease lift when used to trim,
- They are located at the wing tip where boundary layer flow separation may occur,
- They are needed to act symmetrically and asymmetrically to respond as both control units which reduced the control effectiveness leading to less manoeuvrability.

An alternative to elevons is the inboard flap which has better performance effects but less effective as elevons. Pitch control is a major issue in this design as the control surfaces will have to be designed so that it is controllable. With the small lever arm seen in this type of design the forces acting on the control surfaces will be high and will therefore will be slow giving reduced manoeuvrability.

With tailless aircraft there are always vertical stabilizers with a rudder control surface. This is not present in the design and future work will be needed to design this component. Vertical stabilizers generally point upwards but they can also protrude downwards located near the back of the aircraft. If they are positioned at a slight angle the rudder could act as a ruddervators. With twin vertical stabilizers on take-off if the rudders are both positioned inwards they can increase pitching moment. Winglets can also act as vertical stabilizers as seen in the Rutan VariEze aircraft (Aviastar.org, 2010). Some research has been done into fluidic flight controls but this may not be a good application as it would be highly intricate to create, making the manufacturing costly in this type of MAV deisgn (Crowther, 2009).

D. Stability Modelling

The Black Widow MAV (Grasmeyer and Keennon, 2001) stated previously is a perfect example of a constantly changing design for continuous development. This progressive development is seen across all MAV's and some go into extreme detail seen with the Black Widow. As there is a lot of development being done in this area a suitable and quick method should be found with the required accuracy that is needed with this type of design. Using flight simulators is an ideal approach however the accuracy is yet to be proven for Low Aspect Ratio, Low Reynolds designs. Stability can be tested in this type of software and testing should be ideal as the pilot will be in the same conditions as flying in terms of view points and controlling the aircraft to the desired altitude or heading.

Stability can be observed when an aircraft is disturbed about its equilibrium at which the aircraft can be seen to return to its original flight path. Stability affects the manoeuvrability and controllability of the aircraft. An autopilot system can be used to provide active stability but for an MAV it is ideal for the aircraft to be inherently stable as there minimal cargo load can be carried. Stability is affected by aerodynamic characteristics, propulsion systems and structural strength. The focus on stability will be in the longitudinal axis as it is critical for tailless aircraft to be stable (Stanford, 2008). The static stability of an aircraft is depicted by the location of the CG and is the initial response when the aircraft is disturbed from a given angle of attack (pitch stability). The aircraft is statically stable when the static margin is positive meaning the aerodynamic centre is located behind the CG (Raol and Singh 2009) (1.1).

$$\text{Static Margin} = (\text{Aerodynamic Centre} - \text{CG})/\text{MAC} \tag{1.1}$$

It is noted that for symmetrical airfoil its aerodynamic centre will move forward with increase in AOA and aft with decrease in AOA. This means that when the airfoil increases AOA the leading edge will lift and gives the wing an unstable quality. For the majority of aircraft, placing the CG forward of the aerodynamic centre the aircraft becomes nose heavy, this then requires a downward force from the horizontal stabilizer (negative AOA) to become balanced during flight this force will be demonstrated by the inverse camber seen in the wing design.

Dynamic longitudinal stability refers to the aircraft response over time when disturbed from a given AOA (Pitch stability). Longitudinal stability will be the main investigation in this report using an elevator deflection but lateral stability can also be tested with elevons for further research. When analysing the longitudinal stability the short period and the phugoid oscillations must be analysed. The short period oscillation takes place when a rapid vertical gust or pilot induced elevator movement occurs. This is when the elevator moves away from the trim position and back again. This motion will result in a change in AOA that will change the lift, drag and pitch resulting in an oscillation. This oscillation should be heavily damped lasting only a few seconds. The Phugoid oscillation is of low frequency and highly damped motion and has a typical period of 40-60 seconds or longer. It occurs when there is an interchange of energy from kinetic to potential in a level flight condition disturbing the level flight condition. There is a large change in velocity, pitch angle and altitude but not AOA. The motion is so slow that it affects the inertia and damping forces are very low. To test for the phugoid oscillation the pilot can input a pulse command of roughly 10-15s keeping the thrust constant and then allow the aircraft to go through two complete cycles for roughly 2-3 minutes before re-trimming. The pilot usually corrects for the oscillation without being aware of it occurring.

Niño et al. (2007) looks at a much larger MAV (40cm wing span) than that seen in this design to identify the longitudinal dynamics for a given flight condition using its elevator control surface and also lateral dynamics with aileron control surface deflection using the frequency domain identification approach. This is highly analytical and relevantly accurate yet time consuming and if the design was found inaccurate the alteration to the model would be highly time consuming. Cosyn and Vierendeels (2007) look at the overall design of fixed wing MAV's including the dynamic analysis and flight simulation modelling. This project expands on the design, modelling and the control aspects used to stabilise the aircraft. Research in the stability characteristics of MAV's is limited; advances in this area could result in fully autonomous operational flights. If the MAV can become self-governing there would be no need for a pilot and they could act as drones.

Milbank et al (2005) gathered atmospheric data conditions specifically to model the conditions that MAV's would experience. This accuracy is highly complex and detailed. The tests used MAV's of varying wing span, including taking wind gusts of <10m/s at a height of 4 meters above the ground with a 0-10m/s Indicated Air Speed (IAS) specifically analysing the turbulent airflow and wing span and aspect ratio effects. It would be ideal for the findings to be created into flight simulation software specifically for MAV's; this accuracy will not be seen on a commercially available flight simulation software package due to the limitations of commercial computer hardware.

Wind gusts can cause changes in direction, elevation and orientation. This unwanted effect is brought upon the aircraft by wind speeds on a normal day of 10 mph at which the aircraft may only be travelling up to speeds of 20mph. The effects will differ depending on the wind gust percentage to that of the mean airspeed of the aircraft. Suppression of the wind gusts is highly important. Due to the small design, the MAV will be susceptible to instabilities from wind gusts at low airspeeds. As this report will look at longitudinal stability the crosswind vector will not be analysed as it affects the lateral stability but the upward gust will affect the longitudinal stability and should be researched.

Flexible membranes reduce susceptible flow separation at high angles of attack (Ifju et al, 2001). This model would ideally be a membrane construction, like that seen in the journal “flexible wing based MAV” (Ifju et al, 2002). Flight dynamic modelling in flight simulators seen in this project do not model this type of wing configuration and some time has been spent trying to work round this difficulty resulting in the decision of leaving it for future research as the task itself it substantial. This is why the wing is assumed to be a fixed plate wing. However the flight simulators used could represent the flexible membrane using the autopilot features to act as the changing wing shape but would be highly time consuming and very detailed, the limitations of the software to complete this task is currently unknown.

MAV research is being pushed towards flapping wing designs and analysing animal’s natural flying patterns. This design is based on a fixed wing however if flexible membranes were to be used to overcome stability issues with wind gusts is the ideal material for this type of design.

Bee studies are currently being led by the University of Washington to analyse flight path and control during flight (Physorg.com 2010). Experiments consist of wind tunnel testing environments with high speed cameras analysing the movements of the wings. It was first assumed that bees should not be able to fly according to conventional aerodynamic laws. Unsteady viscous fluid dynamics shows that insects rely on vortices to keep them aloft (Cornell News, 2000). The vortices seen in this design will only occur during the first few seconds of flight that will cause the wing to become unstable then disperse into the slipstream. Evidence of how insects use these vortices could be applied to the fixed wing design to convert the annoyance of the vortices into valuable lift.

Figure 9 Bee Flight Control (Physorg.com)

E. Flight Simulation

A flight simulator models the flight dynamics of an aircraft and displays the data as an output. The following researched flight simulators output with visual graphics and can also output numerical data for analysis. This was an important condition for this application as well as usability and accuracy. The chosen simulators will then be analysed against each other for these conditions for the particular need of developing MAV's with fixed wings quickly and effectively.

FlightGear is a highly known piece of software that has had a lot of developers using the software for various experiments and manipulating the software using C++ programming code. Abdunabi et al (2009) has used FlightGear to model a UAV to analyse the autopilot system and the software and the method of programming using JSBSim aircraft configuration files. This was highly successful but it was noted that the aircraft being modelled a conventional aircraft (Cessna 182 RC UAV) which will be much larger than seen in this design. The purpose of being open source software is to give developer's freedoms and flexibility with the software this gives the opportunity to adapt the aircraft design for aircraft development.

Some work has been done to model UAV's using MATLAB and the FlightGear graphical user interface as an output successfully (Turevskiy et al, 2007). This method could be used for MAV's to compare the results gained by flight simulation software programs to look at the ideal calculation methods. This could also be used to compare data to that found from the flight simulators for verification.

Microsoft Flight Simulator X (Deluxe) can be used to create aircraft using C++ programming to create flight dynamics models. It does this using coefficients and data tables that determine the flying qualities of an aircraft. A number of aircraft are included that can be developed for new flight models. It is highly extensive in its calculation methods however it is designed for aircraft not MAV's (Price and Egan, 2006). This software has good resource information however the flexibility of the software is limited unlike FlightGear.

Advanced Aircraft Analysis is a stability and control design software package that looks at the preliminary design phases created by DarCorporation. These include weight, aerodynamics, performance, dynamics, structures, stability and control, load, geometry, propulsion and cost analysis (DARCorporation, 2009). It is not however a flight simulator and may be better for looking at initial comparative designs and not to evolve a unique design. Information gained from using this program could be useful for exporting aerodynamics data as it is based on the classic coefficient build-up method as well as stability and control outputs. This software could be used to find relevant data to import into a flight simulator but for the cost of the program the data can be found if some previous knowledge has been gained from aircraft design. If this was not the case then this type of software could be developed for this type of application as an attachment to a MAV flight simulator.

Due to MAV design being a relatively new concept and a growing field of study the complexities of the designs has not been researched in this particular way however there is scope for possible development. Craighead et al. (2007) did a survey to test commercial simulators capabilities to simulate Unmanned Vehicles of both full and micro scale. They found that the there was no need to build a new flight simulator from scratch to account for the reduction in size so that more research could be done into development. With this in mind the following described simulators were chosen to find out the scope of their software for the particularly complex design seen in this report.

Flight Simulators

The flight simulators used in this report are Merlin (2010), FlightGear (2010) and X-Plane (2010), each have specific design features and have not been specifically designed for MAV's (Table 3). They were chosen due to the expressed ease of use, availability, flexibility of the programming and the variety between the programs. There are two open source software programs and one available at a significant cost but available for this project. It will be of interest to note the differences positive and negative between all three simulators and their cost. This process will highlight the capabilities of the software and what each can bring to the development and productivity needs specifically for MAV's. A significant contribution of this research includes the modelling of micro-scaled input variables and their corresponding output response. Due to the detail of the MAV, the software needs to handle vast amount of data to provide accurate aerodynamic behaviour, this will be limited by the flight simulation software and capabilities. The equations used within the FDM's will also affect the outputs response of the airframe.

Table 3 Flight Simulation Software Summary

Flight Simulation Software	Description	Configuration of Flight Dynamics Model	Description
Merlin	Designed for University use for aircraft design development.	Excalibur	• Coefficient method • GUI to input variable data • Input gain via auto pilot • University owned manual and contact with supplier • Variable weather
Flight Gear	Open-source, under general public licence	JSBSim Others available	• Coefficient method • Can input PID controllers, gain and filters • C++ coding • Online Manual and user guides • Variable weather
X-Plane	Demo, flight time 10 minutes	PlaneMaker and AerofoilMaker	• Coefficient and blade element method • Online Manual and user guides • Variable weather

Merlin Flight Simulation group supply motion based flight simulators used in UK Universities (Zyskowski, 2003). With this software the programming can be altered with C++ coding. This can also be used for step inputs for the control aspects of this project. All variables can be output by this software from a flight allowing for interpretation for control purposes. The autopilot can also be manipulated and used for control inputs such as step inputs. The simulators operate a GUI named Excalibur with versions 1 and 2 to change the aerodynamic model. This simulator models the aerodynamic forces and moments by the classic coefficient build-up method. Version two allows for ten various horizontal and vertical panels; this gives flexibility in aircraft configurations. There is a manual available with function explanations and evidence for how the aerodynamics is calculated but no other information is given but contact from the supplier was available during this project. Some weather conditions in this software can also be simulated and operated from another GUI that can also control fuel amongst other aspects of the flight.

FlightGear is an open-source multi-platform flight simulator that supports many aspects of weather needed for this project (Reissman and Garcia, 2008). FlightGear acts as the Image Generator and FDM. Due to the open architecture it is possible to interface with external scripts and code to produce a unique FDM. There is a wide range of FDM software libraries that can be used; these include JSBSim, YASim and UIUC used to compile configuration files to run in FlightGear (Grasmeyer and Keennon, 2001). A manual for this software is available and is helpful in most areas. JSBSim was created to model flight dynamics and control of aircraft in C++ as a data driven 6DOF simulation application. DATCOM+ has previously been used when working with FlightGear (Jung and Tsiotras, 2007) for numerical modelling of aerodynamic derivatives but again is complex but a range of available resources are available. JSBSim was chosen for this report due to the large selection of available resources and the coefficient calculation method. JSBSim Commander is a Graphical User Interface (GUI) that would ideally be used to reduce the time to input data and improve usability with the software.

X-Plane is a flight simulator that has a free demo version that allows 10 minutes of flight. This however should not affect any results as an MAV flight tests are not likely to exceed ten minutes. This program runs from inputs from Plane-Maker and Aerofoil-Maker these are separate GUI's. Files created by Aerofoil-Maker are used in Plane-Maker. It is a particularly difficult to input data into this package and is more of an estimation of variables which is not detailed enough for this project. It may be easier to not use this and input aerofoil data into the relevant file type needed. Plane-Maker states that it uses blade element theory and the coefficient build-up method to calculate its forces on each element to create output velocities and positions (OpenCFD Ltd, 2004). This method is highly similar to Excalibur used by Merlin however the fuselage can be input from a Computer Aided Design (CAD) file and edited in this software. It is difficult to enter data for a wing of the particular shape needed in this project, if the method used for the fuselage was used for the wing it would be an ideal package to use. X-Plane has a manual and several online help guides such as tutorials and blogs, the manual also states that you can change the weather to specific categories and change wind and turbulence (Pelletier and Muller, 2000). It also runs a briefer which informs the user of the weather information at various airport locations.

Flight Dynamic Modelling Calculations

All three flight simulators that have been chosen compute from coefficient derivatives and these will have to be computed outside the flight simulator software. The chosen software should be quick and simple to use with accurate results. Accuracy is normally the compromise to usability however this report will look at the ideal software to be used for this application and to not compromise excessively on accuracy. Two software programs that were chosen for this project were XFOIL (Dela 2008) and JavaFoil (1996).

XFOIL software reads aerofoil geometry plots and produces coefficient data based on potential flow and boundary layer analysis. It does this by simulating incompressible and viscous flow. The XFOIL simulation is a two dimensional model and does not include chord length or aspect ratio. This will affect the results as the wing has tapered trailing edge due to the Inverse Zimmerman design which will create a changing cross sectional geometry plot along the span. Ideally to overcome this, the wing section would be broken down into sections and the cross-sectional shape will be analysed individually. JavaFoil like XFOIL reads aerofoil geometry plots and produce coefficient data based on potential flow and boundary layer analysis. However the JavaFoil results are not conclusive as they cannot model laminar separation bubbles and flow separation which occurs with this type of wing design.

X-Plane prises itself in the media that it computes using Blade Element Theory (BET), but do the other simulators use the same theory and if not how do they do it? BET is originally derived from Momentum Theory for estimating the Thrust Drag and Power assuming that the forces acting on the blade are uniform. BET however takes into account each section or component of the blade individually, accounting for tip losses and twist, as the loading across the blade will not be uniform (Johnson, 1994). This analysis becomes complex and time consuming but highly accurate. Because of the shear increase in calculations X-Plane would have to run at a higher computation rate if the model becomes highly accurate. In X-Plane the rotors are not the only component that is broken down into sections but the theory is applied to the wings, horizontal and vertical surfaces. The maximum number of sections per wing is 10 which are repeated identically on the opposite side.

Merlin Excalibur I program simulates the wing as a complete section and the engine and prop configuration is not broken down into components. This would mean that the detail of this software should be lower than that of X-Plane. The engine does however have a thrust lapse table but needs more explanatory information on the calculations of this section. Recently the Excalibur II program has had an upgrade and can now compute wing sections as horizontal or vertical stabilizers that can be broken down into ten sections again mirrored on the opposite side. The drag section for the fuselage has also been upgraded to simulate drag at different angles to the airflow and a rotary section has been added (Merlin, 2011). This new upgrade should mean that the simulation detail will be higher than X-Plane but again more detail and time will be needed to program the data and find the required data needed.

FlightGear is a highly flexible piece of software but it has no consistent required information needed for every simulation. The propeller can be broken down into thrust at each section of the blade and by using Aeromatic (2010) this can be computed for the user. The horizontal and vertical stabilisers must have a given area and reference length but no further detail is taken further from that which should mean that the detail will be less accurate unless the three dimensional coefficient data is used. The engine detail again can be very small with just a wattage input which could heavily change results data. Because of the flexibility with this software it could be used to manipulate results and calculations could be submerged into the calculations to include detail.

Table 4 Literature Review Summary

	Research Completed	Areas of research development needed	Research aims during this project
MAV's	MAV's have been developed for civil and military applications in rotary, fixed wing and flapping wing designs. The most complex but lightest design is the Delfly MAV weighing only 4grams. A need for control systems has been raised due to small designs and wind gust instabilities.	MAV applications are extremely different and designs should be fit for purpose. Some aircraft are required to be flown outdoors but specific requirements needed for this to be possible have not been highlighted.	This project will look at the possibilities of modelling in outdoor environments such as wind gusts and atmospheric condition changes. Also the opportunity to look at the handling qualities with a control system to cut product development time.
MAV Stability Design	Zimmerman/Inverse Zimmerman and Camber/Inverse camber designs have been specified as ideals for Low Aspect Ratio (LAR) and low Reynolds designs. The development of flexible membranes for fixed Low Aspect Ratio (LAR) wings has been performed to minimise wind gust instabilities. They have been tested in wind tunnels and Computational Fluid Dynamics (CFD) simulation software.	The Zimmerman/Inverse Zimmerman and Camber/Inverse camber designs have not been combined and used with flexible membranes. Modelling needs to be carried out to analyse the change in camber with different Aspect Ratio (AR) wing designs with the flexible membrane.	Research should be carried out to show the characteristics of an inverse Zimmerman, double camber design. The ease of modelling this particular complex design should be found. The possibility to model a flexible membrane in a flight simulator should also be highlighted.
MAV Stability Modelling	Some models have been simulated to test the stability but larger than that seen in this design. No method has been employed to increase productivity, just highlighting the possibilities. Other factors highlighted wind gust and environmental testing. The research boom is currently towards the flapping wing deigns.	The development time for MAV designs should be reduced whenever possible. The design should always be modelled accurately before prototyping to reduce the cost of creating prototypes that do not work and are unfit for purpose.	An MAV wing design will be modelled in a flight simulator to find out if it will speed up the design to manufacture stages for creating an MAV design. It will also look at the accuracy and limitations of using them as the only tool to test the longitudinal stability of the design. It will analyse the possibility of wind gust modelling and the accuracy.
Flight Simulators	Flight simulation software for MAV development is minimal and none for the complex design seen in this report. Some flight simulation software specifies that they can model UAV's as they have been adapted from larger aircraft analysis. They however have few models that are of the required MAV size. Flight simulators that have been researched use either the Stability Derivatives and Blade Element Theory methods.	MAV simulation software should be developed for their specific flight conditions and the micro-scaled input variables that are required to model an MAV accurately. The best flight dynamic method for MAV simulation should be changed or created for this need.	Analysis of a range of current flight simulators will be carried out to see if they are feasible to simulate MAV flight characteristics. Each flight simulator simulates flight dynamic models differently. Improvements that could be done to the software to increase the accuracy will also be specified in this report.

III. Methodology

F. Equipment

To be able to model the MAV design in a flight simulator the coefficient data must be gathered from relevant Computational Fluid Dynamic software. This report will look at using open source software that should be quick and easy to use to speed up the development process, these include XFOIL (2008) and JavaFoil (1996). However some previous work has been performed by Coventry University members of staff using a more complex program OpenFoam. This data will be used later in the report to validate the results and to show how time dependant CFD information should be incorporated into flight simulator programs.

The simulation software for this project covers three different flight simulators and their Flight Dynamic Models (FDM's). All three simulators were chosen because of their capability to simulate low Reynolds number and a LAR airframe. They include the Merlin Flight Simulator running Excalibur, FlightGear running JSBSim and X-Plane using PlaneMaker and AirfoilMaker.

Due to the detail of the MAV, the software needs to handle vast amounts of data to provide accurate aerodynamic behaviour; this will be limited by the flight simulation software and capabilities. The equations used within the FDM's will also affect the output response of the airframe. The software chosen are vastly different in term of cost, computation method and usability. The results validity is dependent on the users understanding of the software. The available resources to help the user should be researched in terms of usability and time costs for the user.

G. Set Up

The following information should provide the reader with enough relevant information to be able to use the software described and any other useful documentation. The original environment settings of Re = $6x10^4$ and U = 5 m/s were used to model the wing through a range of AoA needed for the flight simulator programs.

XFOIL

The XFOIL 6.9 User Primer (2001) covers the vast amount of inputs that can be used and the scope of the software. For this application the following setup included loading the software from the XFOIL (2008) website and creating an airfoil coordinate file and saving it to the XFOIL software bin folder. This required the X and Y coordinate starting from the trailing edge, round the leading edge returning back to the trailing edge in either direction. Selecting the application XFOIL will run the software and then the airfoil file can be used for testing. This software is written in FORTRAN. To perform the simulation follow the flowing steps selecting entre after each step.

Table 5 XFOIL Running Simulation Steps

Step 1. load (coordinate_file.txt)	Step 9. (Ncritical)
Step 2. oper	Step 10. Exit VPAR
Step 3. visc	Step 11. c 0.0
Step 4. (Re)	Step 12. ! (until it converges)
Step 5. m	Step 13. PACC
Step 6. (Mach number)	Step 14. Out.txt
Step 7. VPAR	Step 15. as (α_{min} α_{max} $\alpha_{increment}$)
Step 8. N	Step 16. PACC

JavaFoil

JavaFoil (2010) is an online applet that can be downloaded or used online. The JavaFoil online manual was used to refer to for the set up and running of the program and was found on the same website as the applet and is easy to follow. To use the program a coordinate file must be created to run in the applet, this should contain the X and Y coordinates, starting at the trailing edge round the leading edge returning back to the trailing edge in either direction. Running the file in the JavaFoil applet analysis in different flow regimes can be completed.

Merlin Flight Simulator

This report uses the Merlin Flight Simulator MP521 which runs the Excalibur Editor I. The layout consists of three visual screens, two instrument screens, one touch screen control panel, joystick, two throttle control sticks and rudder pedals. This software is not commercially available and access to this software is only available through the supplier. For this reason the installation procedure will not be highlighted in this report. The program Excalibur Editor II allows the modelling of horizontal and vertical surfaces into sub-sections. Due to the complexity of the reflex wing and the availability of the comparable results the airfoil data will be modelled as one tapered horizontal surface. If the wing was to be split into the camber and reflex camber further analysis would be needed into the modelling effects of these two surfaces in close proximity and the differences in the modelled values. This does make the editing simpler for the user but some detail will be lost in the uniformity of the camber % along the wing.

Load and Edit

The main control window (figure 10) is seen outside the flight simulator at the control desk. Using the Load Model button under the heading flight model you can load a previous model and use this as your template. Ideally the cessna172MGK.mdl would be used as this is the original model provided with the simulator and should not contain any major faults. Using the Edit Model button in the same section Flight Model you can open the Excalibur Editor to edit your model (figure 11).

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Figure 10 Merlin Main Control Window

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Figure 11 Merlin Excalibur Editor 1

The editor will load on the CG and mass parameter page, using the tabs at the top of the interface you can move across the main sections including wing, aileron, fuselage, airbrake, tail plane, propulsion, undercarriage, systems, diagnostics and tuning. The values of your aircraft can be edited by simply selecting the value and re-typing your new values. It is important to note that the model uses airfoil files (.afl) to read the coefficients of lift drag and pitching moment against angle of attack. This file can be created in a program such as notepad (text editor) and renamed as an .afl file. The airfoil file and the model file must be contained within the flight simulation folders as seen in figure 12.

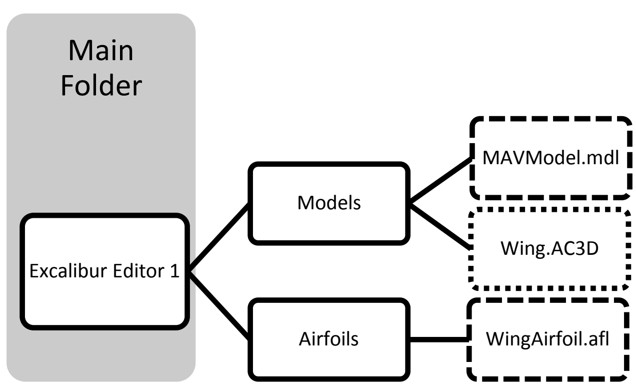

Figure 12 Merlin Configuration Files Layout

With every change of your model it is advised to save the model by selecting the apply button located in the bottom right corner, this will then resume to the main control window where you will have to select Save Model and save the model under a new name. You model must be saved in the selected original file location within the flight simulator program. The image file needs to be in DXF format which can be created in programs such as Solid Works, CATIA or the open source software such as AutoCAD.

Running the Simulation

Once the model has been saved the design can be run for testing. On the main control window there are three buttons in the simulation control section these will be used to start and end the simulation. Firstly start the simulator by selecting Init and the reset conditions interface will load. This is where conditions such as location, speed and the aircraft configuration can be set. Once set and ok selected the match control interface will load and this is the opportunity to check that the settings you have chosen are correct, select ok to approve (disapproval also select ok and select Init again). Finally select run on the main control window and the simulation should start. Make sure the pilot is ready if setting the aircraft in the air at this moment.

The simulation can be run with or without a Head up Display (HUD). The content of the HUD is fixed containing thrust percentage output, climb/descent rate, speed, position headings, aircraft configuration settings, sideslip and g rating.

Outputting Data

To output data you must select export data on the main control window under the heading data recorder. This will ask you to save the file to your chosen location. You can only do this after your simulation has run so that all data is included. You can also select event markers during your simulation; this is best done by another person other than the pilot. The output file will be a string of time dependent data in the form of a text file.

FlightGear

This report uses the Flight Gear which runs xml file coding in the format used by JSBSim. JSBSim is an opensource Flight dynamics Model (FDM) software library and can be run with FlightGear and OpenEagals.
The first tip for this program is to read The Flight Gear Manual (2010) it will teach most things that you will need to know to program your xml configuration files. It will include such things as how the programming style works and how units must but be kept constant and how to input calculations. It is a complex method compaired to Merlin however there are good examples to work from and available models created that can be used for editing.

JSB Commander was not used for this model due to the errors and missing components when creating a model within this GUI for FlightGear. Not all aspects of an aircraft were created in this model but further developments would be easily produced.

Loading and editing your model

The first step is to download and install the open-source program to your C drive and look at other models that have already been created. These can be downloaded from the FlightGear website in most computer formats. The format seen here is the Windows version v0.9.10.

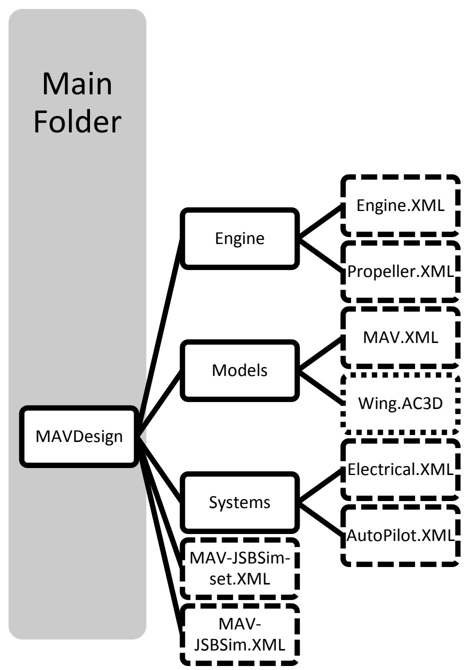

Figure 13 FlightGear Configuration Files Layout

Once you have downloaded the file open the file; C: Program Files/Flight Gear/data/Aircraft. From this file you can explore all aircraft that have been included with the software. When viewing your files I recommend using Notepad++ v5.6.8 (Don Ho 2010) which was used in this process as it keeps the layout of your work clear and is also open-source. To source other aircraft files it is recommended to return to the FlightGear website and source files from this location which is where the Rascal110 file was downloaded from for this project.

To edit a model first create file with the corresponding aircraft name and copy your aircraft data to here. The files used must be located in the correct folders and in the programming referred to the correct location. It is critical when programming to set the names of the folders and keep them the same to prevent mistakes.

In figure 13 folders are highlighted, identifying the different programming files and image files. They are named so that the content can be easily identified within the programming. This main file for the aircraft design is located in C: Program Files/Flight Gear/data/Aircraft/MAVDesign.

Running the Simulation

Once the data has been correctly input and saved you can load the FlightGear program from the application icon this will then go through a series of loading screen to set various data.

The first loading screen will ask to select your model and select next to then select your location. You will then be asked to set up any other settings such as screen resolution and time of day for the flight. Within this window you can also select advanced settings; this is where you can select things such as wind direction, the type of model program type; jsbsim or the input output capability. Once all variables are set select Ok and Run this will initiate the simulation and load the model.

When the model has loaded the simulated view should contain a pilot eye view, you can alter this using the tool bar and selecting the View tab to the chase view (figure 14) depending on if the MAV to be modelled has an onboard camera this change of view is very useful.

Figure 14 FlightGear Chase View

Inputs to the program can be in the form of keyboard or a joystick. The commands when using the keypad can be found in the Help tab. It is ideal to have a copy of the key commands to start with giving a list of necessary commands such as pitch, roll, yaw, brake on/off and throttle up/down.

Outputting Data

There are two methods to output data, firstly within the program and the second to create an xml file that the program reads and exports the required data.

Figure 15 FlightGear Logging Box

To export data within the program select the file tab on the toolbar and select logging, this will open up a box (figure 15). Within this box you must change the log file section and enter to drive location for your file, it is also noted that if you change your file to fg_log(test_number).csv the file will not be over written. Make sure that logging enabled is selected. You must select the boxes that you wish to record and enter any other native property such as the following stated found in the FlightGear/data/Docs-mini/README.properties (open with Notepad++):

/orientation/roll-rate-degps
/orientation/pitch-rate-degps
/orientation/yaw-rate-degps

Alternatively as this only allows the user to extract nine data strings, an xml file can be created allowing more native properties to be recorded. This file should be placed in the protocol file within FlightGear, an example is shown in figure 16.

```
<?xml version="1.0"?>
<PropertyList>
<generic>
   <output>
       <line_separator>newline</line_separator>
       <var_separator>tab</var_separator>

       <chunk>
          <node>/position/altitude-agl-ft</node>
          <name>altitude to go</name>
          <type>float</type>
          <format>%03.2f</format>
        </chunk>

       <chunk>
          <node>/orientation/heading-deg</node>
          <name>Heading</name>
          <type>float</type>
          <format>%03.3f</format>
        </chunk>

   </output>
 </generic>
</PropertyList>
```

Figure 16 FlightGear Protocol xml file layout

This file is then referred to when initialising FlightGear from the advanced section, from the input/output tab. Here FlightGear must be directed to the file so that it can read it this is done by the following format by selecting the dropdown boxes to read the following;

--generic=file,out,20,flight.out.output

File - tells flight gear to open a file, out – to use a socket to output data or transmit, 20 – at a rate of 20 times per second, flight.out – name of the new output file, output – using the xml file name. When typing the required file names, make sure there are no spaces.

X-Plane

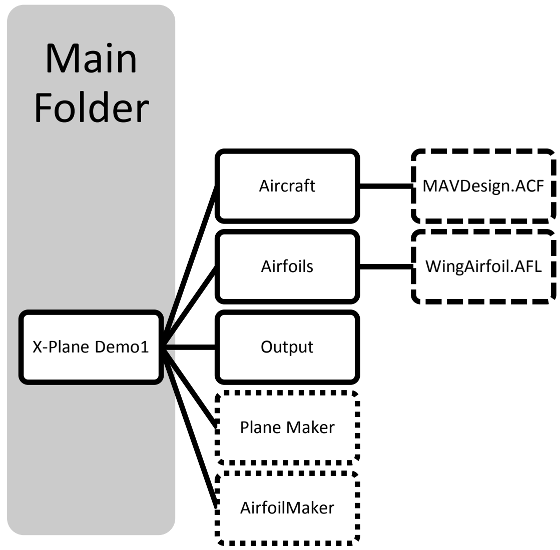

Figure 17 X-Plane Configuration Files Layout

This report uses the X-Plane9.0rc3 Web Demo version which includes PlaneMaker and AerofoilMaker. This can be downloaded directly from the X-Plane website and with this version you can the keyboard/joystick and 10 minutes of flight time only.

Once you have installed the program onto your computer it will be contained within a file. This file will contain the flight simulator program (X-Plane9), the model editor (PlaneMaker) and the airfoil editor (AirfoilMaker) (figure 18). It will also contain the important files names; aircraft, airfoils and output. The aircraft folder is where all the aircraft files are located and they can be opened in PlaneMaker. The airfoil folder includes airfoil files that can be opened in (AirfoilMaker or Notepad++). The output folder contains any saved flight data that has been recorded during your flight simulation in X-Plane. In figure 17 it shows the layout of the main folders that should be used for editing; folders are highlighted including file editors and input files.

Loading and editing your model

Firstly open an airfoil file in AirfoilMaker and modify the file so that you can then use it when creating your aircraft in PlaneMaker. The main toolbar along the top of the editor will allow you to save load and create a new file. Within the program contains another toolbar that will allow you to change the view of the graph from 20 to 180 degrees to view your coefficients. This is a helpful tool as it allows you to visualise your data. The toolbar also contains finite lift/drag and camber. This tool is difficult to use and difficult to manipulate the data as it is very restrictive. Using Notepad++ to edit the data is easier but you must be careful not to open it up in the AirfoilMaker program as it may change the variables.

Start creating your model by using a previous aircraft model using PlaneMaker and change the inputs step by step saving after each modification. The original model used in this project was PT60RC. This file was located from the X-Plane forums. In the standard toggle toolbar you can change things such as viewpoint, engine specifications, and aircraft dimensions including miscellaneous parts, landing gear, weight and balance. With PlaneMaker you can chose the instrument panel and its layout unlike the other flight simulators seen in this project. In the expert toggle toolbar you can select the aerofoils, input artificial stability as well as weapons.

Running the Simulation

To run the model that has been created, open the folder and select X-Plane9 this will begin to run the program. Once the program has loaded the aircraft must be chosen from the dropdown toolbar located at the top of the screen. Select Aircraft then Open Aircraft and find your aircraft in your specified folder location. Once you have chosen your aircraft it is ideal to test you input hardware such as joystick, toolbar - settings – Joystick, keys and equipment.

Once this has all been completed the aircraft can be flown from the loading position from a grass/tarmac runway or set at a desired location such as helicopter pad or in a flying formation. Select toolbar- File- Load Situation and select the desired loading position, these can also be created to suit the programmers and aircraft needs.

The aircraft can be flown with the conventional pilot eye position or can be viewed by a chase/tower view. These are all relevant settings that can be used for an MAV but if no camera is monted a chase or tower view can be used and will make a difference for pilot control.

Outputting Data

Once the flight has been achieved the simulation can be paused by selecting ‘P’ on a keyboard. Once this has been done select the toolbar – File, Load Flight Data Recorder File. Close this selection by selecting the cross at the top of the Flight Data Recorder Box. This will return back to the main simulation screen. It will also have given the user the ability to rewind and pause the flight that has just been completed. The flight can also then be saved by selecting the toolbar- File, save replay. This will save the flight so that you can close the simulator and reopen at a later date and replay the same flight or analyse the data, it is always useful as a backup in case of system failures.

Data can be analysed whilst using this flight simulator and is set for several different testing procedures such as longitudinal static stability. Selecting the tool bar –Settings, Data Input & Output the data needing to be analysed can be chosen.

Firstly in the ‘Data Set’ tab (figure 5) shows all 131 data sets that can be selected and sent to either the Internet, Disk file ‘Data.txt’, Graphical Display ‘Data See Tab’ or the Cockpit during flight. The output file can be useful for plotting further analysis that X-Plane cannot compute whilst the ‘Data See’ Tab can only plot limited data but can plot such things as lift and drag for the desired flight time.

The most interesting ability of X-Plane is the testing settings that are seen in the ‘Flight-Tst’ tab. Selecting the longitudinal static stability test it will select airspeed, pitch input ratio, pitch attitude, left thrust, right thrust and pitch input. Returning to the main screen the flight can be replayed from the start or from a particular point in the flight. Returning back to the Flight-Test tab the required data for that particular test should be recorded.

H. Procedure

The aerodynamic properties of the thin wing were examined using open source software distributed by XFOIL and JavaFoil. The simulations were carried out at a Reynolds number of $6x10^4$ and a freestream velocity of 6 m/s. The wing span is 0.1m with a mean wing chord of 0.1m, with a double camber configuration 5% and 3%. This data was then used to input into the flight simulators Merlin (Exaclibur Editor I), FlightGear (JSBSim) and X-Plane (PlaneMaker and AirfoilMaker). Longitudinal stability tests could be completed to analyse the pitch stability of the MAV design. This data will then be used to give a Flight Dynamic analysis of the model and to compare the software limitations and ability to model an MAV wing accurately. The assessment of the scope of the simulator was assessed for the use of feedback loops to improve the stability. The procedure process can be viewed in figure 20.

Aerodynamic Coefficient Data Collection

The original environment settings of Re = $6x10^4$, M=0.8 and Ncrit= 9 was used in to model the wing design through a range of AoA needed for the flight simulator software. The previous stated setup and running methods were used. As XFOIL can only produce a limited range of data (e.g. -20 deg to 20 deg in steps of 0.1 degree) a repeated simulation was used to build the range of angles needed to create a file with all the needed data for the flight simulators. JavaFoil which can handle more data (-180deg to 0 deg in steps of 1) has to also be repeated as two step increments must be used for X-Plane providing different details across the 360 degree spectrum. The loaded simulation of the airfoil can be seen in figures 18 and 19 for both XFOIL and JavaFoil.

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Figure 18 XFOIL Model Print Screen

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Figure 19 JavaFoil Model Print Screen

Validation

The coefficient data will be validated by the comparison of data to that of other software OpenFoam and published works of a similar double camber design. OpenFoam is open source CFD software distributed by OpenFoam CFD Ltd. Research into the change in camber of the specified wing design seen in this report is also currently being performed at Coventry University by other members of staff. The primary solver used was icoFoam (Zyskowski, 2003); based on the Pressure Implicit with Splitting of Operators (PISO) method. The simulation was performed on a three dimensional model accounting for the change in shape along the wing span. The findings will also be validated against other double camber published research.

Calculate MAV Characteristics and Flight Conditions

Using the Oswald efficiency factor as 0.7 to find k for this wing design (I.1), k can be used to find the drag polar (I.2). This can then be used to calculate the power input needed to be above that of the stall speed.

$$e = \frac{1}{k + p\pi A} \tag{I.1}$$

$$C_{D\,polar} = C_{Dmin} + k(C_L - C_{Lo})^2 \tag{I.2}$$

The aerodynamic derivatives can be found by calculating the gradients of lift drag and pitching moment for the wing in the Normal axis.

Table 6 Aerodynamic Derivatives w (Normal)

Force Moments	Script	Information	Calculated
X (axial)	$C_{D_\propto}$	Important at low speeds	$\frac{\partial C_D}{\partial \propto}$
Z (vertical/ normal)	$C_{L_\propto}$	Lift curve slope –ve implying stall	$\frac{\partial C_L}{\partial \propto}$
M (pitching)	$C_{m_\propto}$	Defines stick fixed static margin and natural frequency	$\frac{\partial C_m}{\partial \propto}$

To calculate the stall speed (I.3) the following equation can be used. This is done to look at the characteristics of the aircraft and then to calculate the necessary power needed for the overcome the stall speed (I.4).

$$V_{SI} = \sqrt{\frac{2mg}{\rho S C_L}} \quad \therefore V_{SI} \propto C_L^{\frac{-1}{2}} \tag{I.3}$$

$$\eta P = \frac{1}{2}\rho V^3 S a + \left(\frac{b(mg)^2}{\frac{1}{2}\rho V S}\right) \tag{I.4}$$

Using the aerodynamic derivatives the pitching moment can be calculated and an ideal pitching moment can be found by assuming a point mass can be used to change the location of the CG.

Table 7 Pitching Moment Variables

Variable	Script
Angle of Incidence	i
Reference distance from CG	X_{CG}
Wing Area	s
Position of Neutral Point	X_w
Mean Aerodynamic Chord	c
Pitching Moment about Neutral point	C_{M_α}
Gradient of Lift Curve	$C_{L_\propto}$

$$C_L = C_{L_\propto}\left(i \; x \; \frac{\pi}{180}\right) \tag{I.5}$$

$$C_{M_{CG}} = C_{M_\alpha} + C_L\left(\frac{X_{CG}}{c} - \frac{X_{AC}}{c}\right) \tag{I.6}$$

Input Data into Flight Simulators

The previous data characteristics were then used to input data into the flight simulators along with the MAV geometry data, to do this the following models were used to manipulate into the required model files (referenced in appendix 2).

- Merlin = Cessna172MK1
- FlightGear = Rascal 100
- X-Plane = GP_PT_60

When creating models in the chosen flight simulator editor, save every modification and keep a clear log book with reasons for the changes so that you can refer back to them. It is also ideal to name your files with a description of the file as well as time and date referring to your log book.

Points that should always be remembered when modelling include the axis orientation, scale rules and units. Axis orientation should always be kept to that specified by the flight simulation software. Merlin uses x = positive forwards, y = positive starboard, z = positive down (Merlin, 2006). Due to the software restrictions scale changes were performed for programs Merlin (1:10) and X-Plane (1:2). Merlin uses SI units which is seen throughout this project however JSBSim can use either format and X-Plane only uses imperial units.

A summary of the data input into the flight simulators can be seen in table 9. The engine/motor specifications were restricted by the airfoil characteristics and were calculated and relevant equipment chosen. The proposed engine and propeller design will be adaptions of those of the original models. The avionics, radio control system and auto pilot system will not be implemented in this report however the design of an autopilot could be developed in all three flight simulator models. Due to the flight simulation software Merlin and X-Plane needing to model an undercarriage table 8 highlights the input ideals that are needed. The elevator and aileron sizing and positioning can be controlled by the programmer to identify the ideal for this design so that the aircraft can perform a suitable takeoff.

Table 8 Undercarriage Inputs

Variable	Value
Track	>90% of Span
X coordinate Main Gear	>90% of Chord
X coordinate Nose Gear	>30% of Chord
Drag Coefficient	0
Reference Area	Minimum as possible
Z coordinate at which drag occurs	0 drag at centre line

Table 9 Input Data Summary

Input	Merlin	FlightGear	X-Plane
Scale Changes	1:10 due to limited minimum mass	No scale changes needed	1:2 due to limited minimum mass
Mass	Fuel mass at coordinates X,Y and Z for full or empty fuel load and payload mass.	Pilot mass and fuel mass at coordinates X,Y and Z for full or empty fuel load.	Point mass by fuel tank locations
Wing Coefficients	Look up table for Cl, Cd and Cm at AoA for any range/detail.	Look up table within coding for Cl, Cd and Cm at AoA for any range/detail.	Look up table for Cl, Cd and Cm at AoA for, full 360 degrees, specific 1 degree increments & 0.1 degree increments (-20 to 20 degrees). Must include other detail including Re and coordinates. It cannot use coordinate points for a cambered wing.
Wing Shape	Area, Setting angle, Span, MAC, TR, AR, Sweep angle, dihedral and Aerodynamic centre X and Y.	Area, span and chord	Area, Setting angle, Span, MAC, TR, AR, Sweep angle, dihedral and Aerodynamic centre X and Y. For a ten section breakdown of ten wing components available
Fuselage	Min and Max Cd, Aerodynamic Centre X and Y, Reference area and length.	Can be added if needed (Area)	Not needed (shape –area, length and drag)
Undercarriage	Track (main), X and Y coordinate, stiffness, damping and preload. Main or Nose Drag Coefficient, reference area and drag Z coordinate.	Contact points needed, frictions, damping, stiffness, steering and retractable	Sizing, location, tyres and strut sizing.
Propeller	Fixed pitch, diameter, efficiency and speed	Diameter, number of blades thrust at points along blade and pitch min and max	Like wing breakdown of each section
Engine	Engine type, Number, Response time, Power, SFC, mounting angle and position.	Wattage	Bhp and settings for graphical feedback such as V1.

Stability Flight Tests

This proposed paper will concentrate on studying the longitudinal response and stability of the aircraft. The variables in the longitudinal axis include velocity and pitch. The flight testing procedure will include step inputs of velocity and pitch.

First a stable altitude and suitable speed must be chosen so that the aircraft is within pilot control. Then the stick fixed and stick free neutral points must be found to find the ideal flight conditions.
Once this has been achieved the longitudinal stability tests can be completed.

Stick Fixed Neutral Point: Fly the aircraft at a given CG location at various speeds and measure the corresponding elevator angle to trim, repeat this for various CG locations. Plot elevator deflection against the CG location, the intersection of the curve with CG axis gives the stick fixed neutral position.

Stick Free Neutral Point: Fly the aircraft at a given CG location at various speeds and measure the stick force at each speed, repeat this for various CG locations. Plot (Stick Force /elevator deflection) against the CG location, the intersection of the curve with CG axis gives the stick free neutral position.

Once the ideal CG location is finalised the main testing can begin. The main testing procedure will involve getting the aircraft to the desired flight conditions as specified by the above procedure and perform one of following two tests. This involves inputting a velocity or elevator input by push the stick forward and letting go as soon as possible. The velocity input will be taken by increasing the throttle by a set amount across the three simulators. The recording process will last 1 minute so that all data is recorded accurately and the phugoid oscillation can be highlighted. From this a wind gust can be applied to look at the effects from a speed of 1-5m/s in a vertical direction.

Table 10 Stability Test

Procedure	Test
Step 1	Chose stable speed and altitude
Step 2	Load the aircraft at a given CG location at various speeds; record the corresponding elevator angle to trim. Plot trim against the CG location, to find stick fixed neutral position
Step 3	Fly the aircraft at a given CG location at various speeds, measure the stick force at each speed. Plot Stick Force/elevator deflection against the CG location, to find the stick free neutral position.
Step 4	Step input velocity, plot oscillations
Step 5	Step input elevator, plot oscillations
Step 6	Step input wind gust 1-5m/s, plot oscillations

To validate the results of the flight simulators the results will be compared to each flight simulator output data. If further validation is to be completed the MAV design specifications could be entered into the MATLAB toolbox in SIMULINK to give a deeper Flight Dynamic and Control analysis. This research has been completed before by Rauw (2001) for the RASCALL 110 aircraft which has been modelled in FlightGear and will be the base to the FlightGear model design.

Simulation Analysis

This section is highly important to this project and will include an analysis of all the flight simulator software and the corresponding features need to simulate an MAV. The completed analysis proforma can be seen in appendix 3 this was used as a basic outline of the comparative study. It will cover such things as the usability, flexibility and suitability for this particular application. The topics include input method, simulation editing, testing and outputting. The analysis will be done as a separate entity to the simulation results as it is independent from modelling the specific deigns stated in this report and generalised to simulation of MAV's and their requirements.

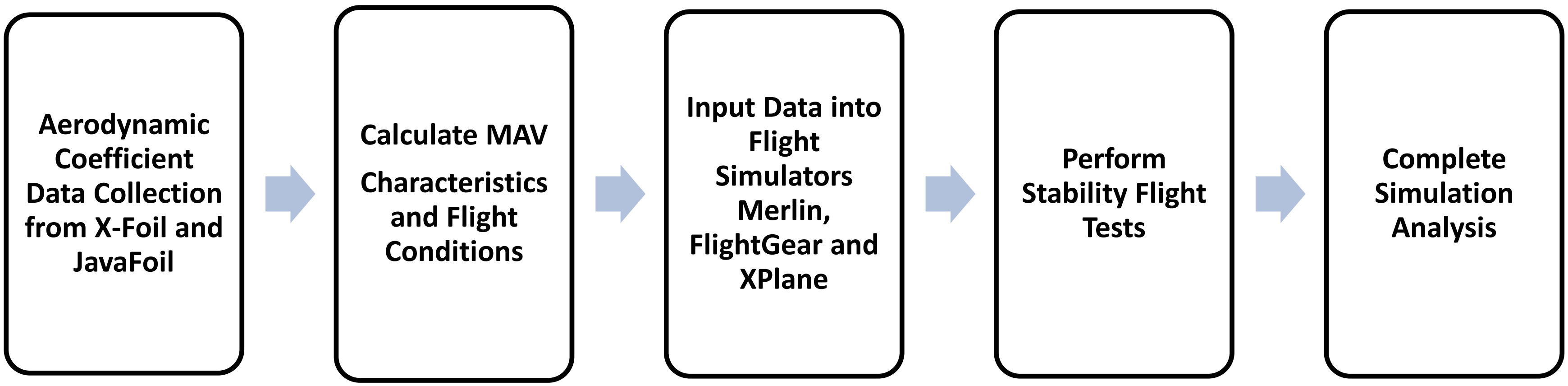


Figure 20 Method Summary

IV. Analysis

I. Aerodynamic Coefficient Data Collection

Results were gathered from XFOIL and JavaFoil initially for the AoA range of -20 to 20 degrees in increments of 0.1 degree (JavaFoil) and 1 degree (XFOIL). This data can be seen in figures 21 and 22.

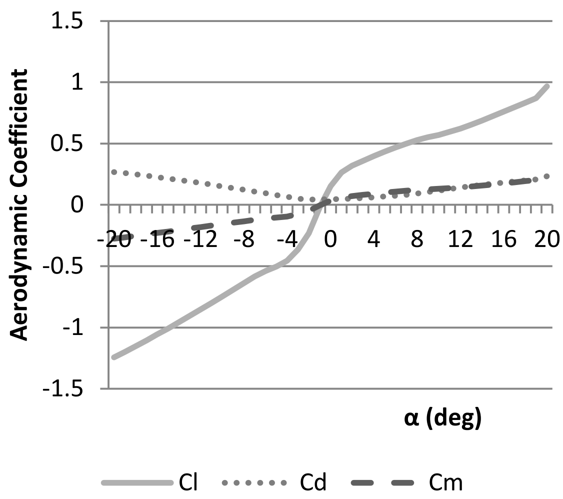


Figure 21 XFOIL Aerodynamic Coefficients (α=-20^{o} to 20^{o})

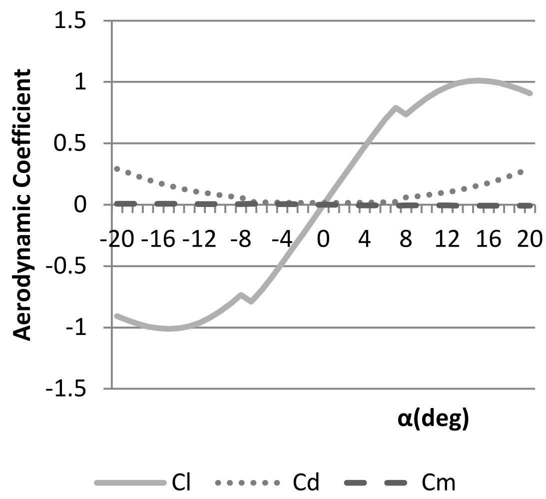


Figure 22 JavaFoil Aerodynamic Coefficients (α=-20^{o} to 20^{o})

Comparing results at first glance show a similarity with the range of values, such that a coefficient of lift of 0 to 1 is seen between 0 and 20 degree AoA. Similarly the coefficient of drag is of a similar curve and range of 0 to 0.25. The most noticeable difference is that of the coefficient of pitching moment which is a positive gradient for XFOIL and straight line for JavaFoil.

Firstly the gradient of the coefficient of lift for XFOIL is 3.513 and JavaFoil of 4.708. This difference is due to the shallow continuous gradient seen in XFOIL that shows no loss of lift in this AoA range. However JavaFoil shows a two points loss of lift, firstly at 8 degrees AoA and 16 degree AoA. The initial loss of lift is a short sharp decrease and is not that expected of a stall except there is also a short sharp increase in drag at the same AoA. The reduction of lift at 16 degree AoA is steady and continuous and a gradient of that expected by stall. This pattern is again repeated in the negative AoA range and highlights the possibility that the cause could be due to the camber.

The gradient of the coefficient of drag for XFOIL is 0.724 and 0.450 for JavaFoil. These again are similar however the major difference is the increase in drag at 8 AoA seen in JavaFoil as stated previously and not seen in XFOIL. JavaFoil also shows a slightly higher drag coefficient at 20 degree AoA due to the larger gradient.

The major difference between the models is the pitching moment XFOIL shows a positive gradient which means that it has not been taken against at the aerodynamic centre but from the trailing edge. Whilst JavaFoil shows a continuous line and shows that it was taken from the aerodynamic centre. This could have occurred because during the process of the simulation of the XFOIL program does not ask the user for a specified location for the pitching moment.

After the completion of the initial AoA range a complete 360 AoA range was completed as per the requirements of the flight simulator X-Plane. This data can be seen in figure 22 produced by JavaFoil this was due to the results being quick to produce and the pitching moment being taken about a point to be moved with ease, unlike that of XFOIL.

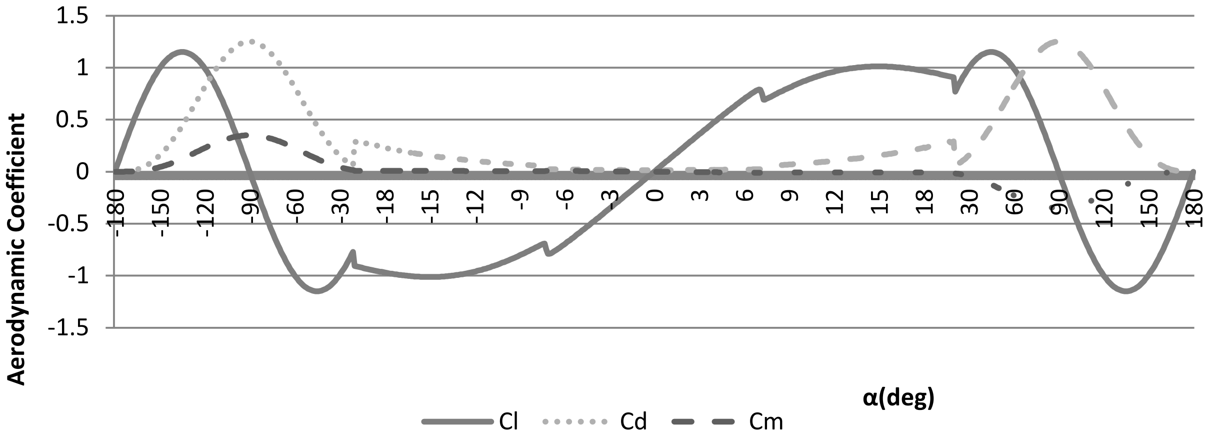


Figure 23 JavaFoil Aerodynamic Coefficients (α=-180° to 180°)

From analysing figure 23 the coefficient of lift in the positive region shows three points at which loss of lift occurs, the third loss occurs at an AoA of roughly 50 degrees. It also shows that the initial stall point of 16 degrees recovers and increases in lift at roughly 22 degrees AoA. This increase in lift reaches a maximum of 1.15 coefficient of lift. This is an interesting occurrence and is also repeated in the negative region.

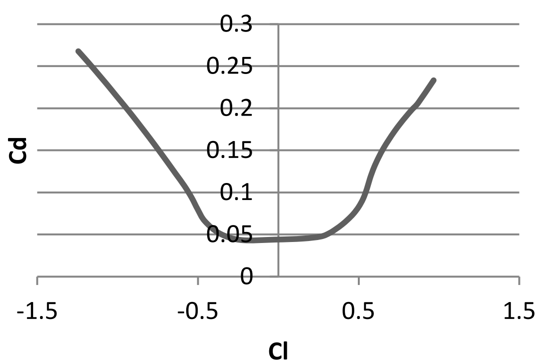
The third increase in lift starting at 22 degrees AoA gives a sharp reduction in drag that is almost immediate, this reduction in drag results in the third increase in lift. The graphs seem to show a sudden reduction or shift to the results at 22 degree AoA with both drag and lift and also a change in pitching moment. This shift should not be anything to do with the repeated results joined together as the range was taken between -20 to 20 and -180 to 180. This again is all repeated in the negative region. Again at 22 degree AoA the pitching moment decreases to 90 degree AoA and returns at 150 degree AoA, this again is repeated in the negative region of the graph.

Calculating MAV Characteristics

From analysing similar MAV designs and the assumed ideal weight of my aircraft is 10g as stated previously. Using the Coefficients data and the assumed weight of 10g the flight characteristics of the aircraft can be initially assumed. The following calculations were calculated in MATLAB with variables of weight and propeller efficiency to find the best configuration for the model.

Drag Polar

By plotting the coefficients of lift and drag against each other the drag polar can be found by using equation I.2. The XFOIL drag polar is $C_D = 0.0435 + 0.3419{C_L}^2$ taken from figure 24 using the table of results created by XFOIL. JavaFoil drag polar is $C_D = 0.01513 + 0.3419{C_L}^2$ also taken from the figure 25 and the associated table of results file created by the JavaFoil output. This shows that there is a considerable difference in minimum drag between the two simulations.



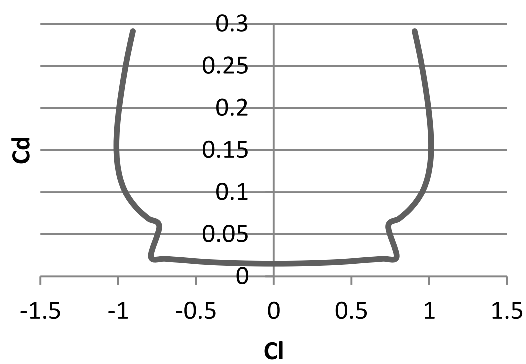


Figure 24 XFOIL Cd vs Cl, range -20 to 20°degree α

Figure 25 JavaFoil Cd vs Cl, range -20 to 20°degree α

Aerodynamic Coefficient Derivatives

The stability and control derivatives can now be determined analytically for Normal (component velocity α). This can be done using the necessary expressions for example $C_{D_\propto} = \frac{\partial C_D}{\partial \propto}$ the derivatives can be viewed by Cook (2007). The expression for $C_{D_\propto}$ is the gradient of drag against per degree of AOA. This can be found by locating the relevant XFOIL or JavaFoil graphs and measuring the converting AOA to radians. The results of this are seen in table 11.

Table 11 Aerodynamic Derivatives w (Normal) XFOIL and JavaFoil

Force Moments	Script	XFOIL	JavaFoil
X (axial)	$C_{D_\propto}$	0.724rad^{-1}	0.500rad^{-1}
Z (vertical/ normal)	$C_{L_\propto}$	3.513rad^{-1}	4.708rad^{-1}
M (pitching)	$C_{m_\propto}$	0.804rad^{-1}	-0.038rad^{-1}

Stalling Speed

To find the stall speed it is dependent on the variables seen in equation I.3 in particular the mass. As the desired mass is currently 10grams the desired stall speed is assumed to be 6m/s to find out if the desired mass is appropriate for the stall speed to be lower than 6ms should be completed. By using this equation the $C_{L_{Max}}$ is used which is different for each aerodynamic simulation program ($C_{L_{Max_{X-Foil}}} = 0.967$, $C_{L_{Max_{Java}}} = 1.15$).

$$V_{SI_{Java}} = \sqrt{\frac{2*0.01*9.81}{1.225*0.00755*1.15}} = 4.3\text{m/s}$$

Or

$$V_{SI_{X-Foil}} = \sqrt{\frac{2*0.01*9.81}{1.225*0.00755*0.967}} = 4.68\text{m/s}$$

From this equation the stall speed for XFOIL is 4.68m/s and only 4.3m/s for JavaFoil. These are highly similar but as JavaFoil's stall speed is lower this maybe due to the maximum lift coefficient occurring at 50 degrees. This may be seen as an error as the maximum lift coefficient for XFOIL is only that which occurs within the range of -20 to 20 degree AoA. Due to this the equation can also be used to plot the data against angle of attack to look at the change in stall angle (figure 26). By doing this it gives an accurate look at the stall effects of the MAV before test flights are performed. This will then help pinpoint a setting angle and flight speed.

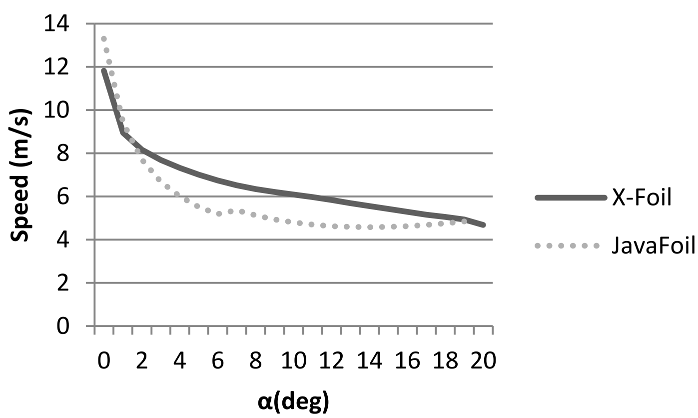


Figure 26 Stall speed against -20 to 20°degree α range at a mass of 10grams

Plotting the 360 degree AoA range (figure 27) the flight range can be shown and the effects of stall such as the gradient at which stall occurs. It is noticed that between 0 to 90 degrees and -90 to -180 the MAV should be able to fly without stalling if the velocity is kept above 5m/s. From this graph the setting angle could be assumed to be 10 degrees so that the stall speed is low. This allows the MAV to travel at lower speeds and therefore need a smaller less powerful engine to power it allowing it to perform within a large AoA operating range. This setting angle will then be assessed for pitching moment, mass and CG location.

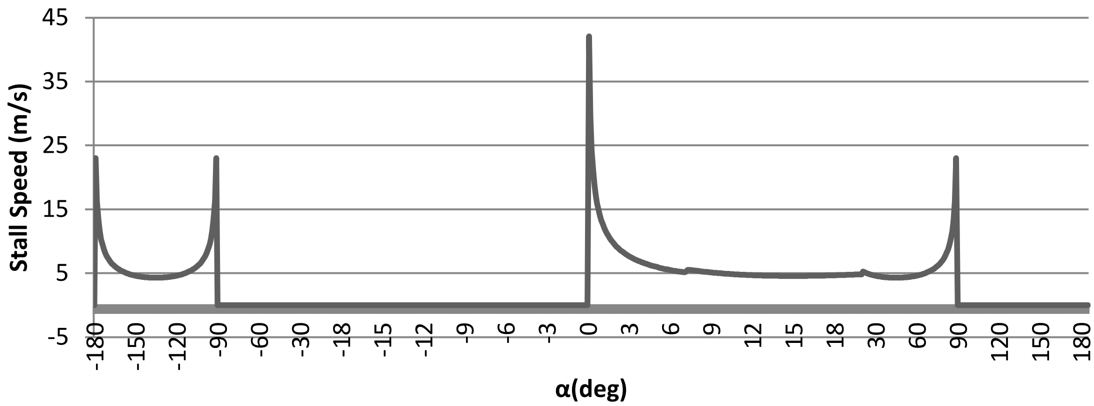


Figure 27 JavaFoil Stall speed against -20 to 20°degree α range at a mass of 10grams

To find the maximum power required to fly the aircraft the equation I.4 was used with the aircraft data assuming a mass of 10g and a minimum speed of 6m/s, assuming power efficiency of 50%.

$$P_{Java} = \frac{0.5x\ 1.225x6^3x\ 0.0755x\ 0.0152 + \left(\frac{0.3419(0.01x\ 9.81)^2}{0.5x\ 1.225x6x0.0755}\right)}{0.5} = 0.326\text{W}$$

or

$$P_{X-Foil} = \frac{0.5x\ 1.225x6^3x\ 0.0755x\ 0.0435 + \left(\frac{0.3419(0.010x\ 9.81)^2}{0.5x\ 1.225x6x0.0755}\right)}{0.5} = 0.893\text{W}$$

Assuming that the MAV is to fly above this speed and with a safety margin so that the aircraft does not stall a speed of 7m/s was used to calculate the power needed giving 0.5W (XFOIL) and 1.4W (JavaFoil).

Pitching Moment

Using data in figures 28 and 29 calculations were performed to find the ideal equipment and corresponding CG location. The following calculations were calculated in MATLAB with variables seen in table 11and 12 to find the best configuration and CG location for the model.

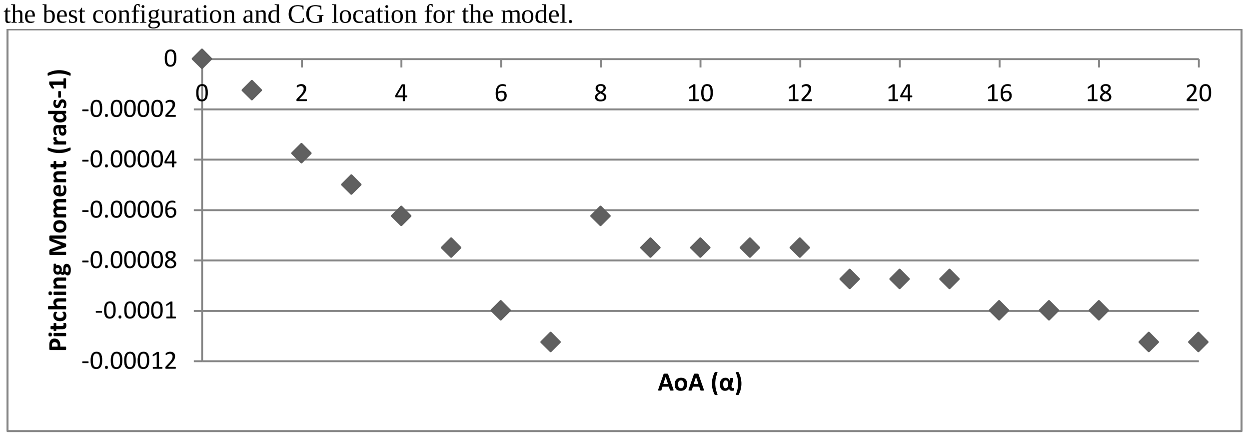


Figure 28 JavaFoil Coefficient of Pitching Moment (rads^{-1}) against 0 to 20°degree α range

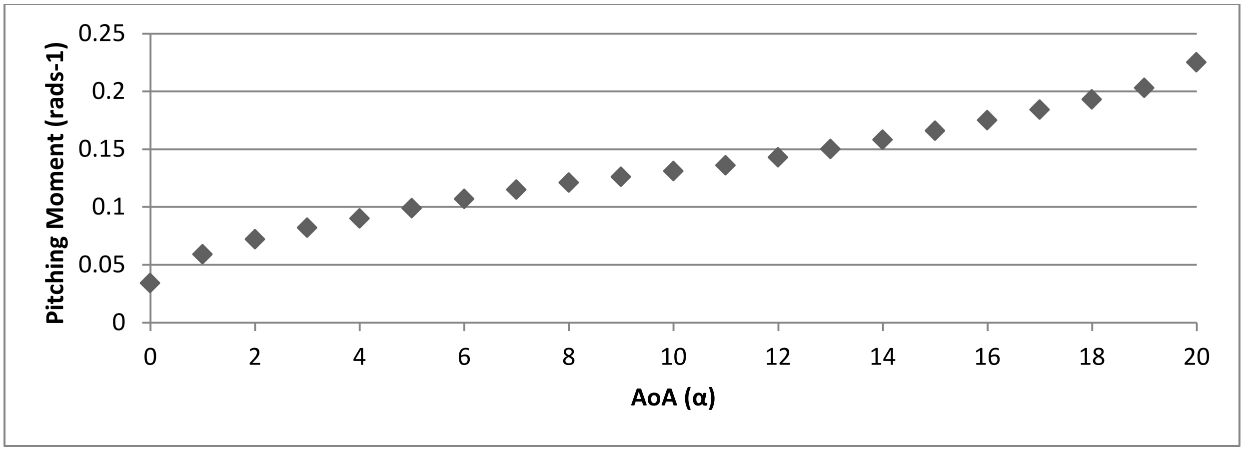


Figure 29 XFOIL Coefficient of Pitching Moment (rads^{-1}) against 0 to 20°degree α range

The pitching moment about neutral point was calculated from CATIA CAD software using the initial design of the wing. Using equations I.5 and I.6 and data from table 11, a X_{CG} location could be found for an ideal pitching moment having a negative static margin.

Table 12 Pitching Moment Input Variables

Variable	Script	XFOIL	JavaFoil
Angle of Incidence	i	0°	0°
LE to CG	X_{CG}	0.02m	0.02m
Wing Area	s	0.00755m^2	0.00755m^2
LE to Neutral Point	X_w	0.04358 m	0.04358 m
Mean Aerodynamic Chord	c	0.0755	0.0755
Pitching Moment about Neutral point	C_{M_α}	0.13Nm	-0.00008Nm
Gradient of Lift Curve	$C_{L_\propto}$	3.513rad^{-1}	4.708rad^{-1}

The following calculations are for an incidence angle of 0 degrees:

$$C_{M_{GR}} = 4.708\left(\frac{0.02}{0.0755} - \frac{0.04358}{0.0755}\right) = -1.47039\text{rad}^{-1}$$
$$C_{M_{GR}} = 3.513\left(\frac{0.02}{0.0755} - \frac{0.04358}{0.0755}\right) = -1.097\text{rad}^{-1} \quad \text{(I.5)}$$

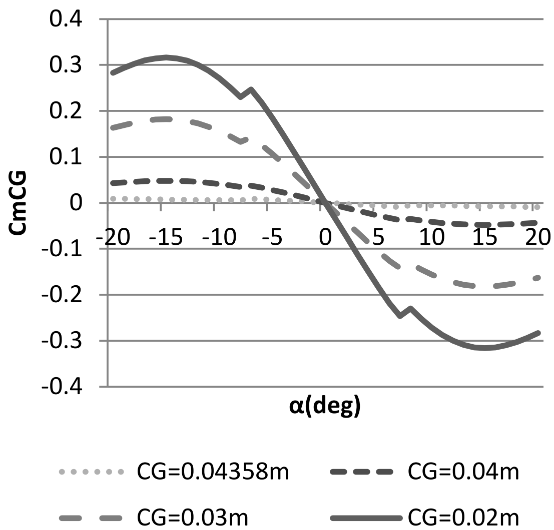
$$C_{M_{CG_{JavaFoil}}} = -0.00008 + 0\left(\frac{0.02}{0.0755} - \frac{0.04358}{0.0755}\right) = -0.00008Nm$$
$$C_{M_{CG_{X-Foil}}} = 0.13 + 0.152\left(\frac{0.02}{0.0755} - \frac{0.04358}{0.0755}\right) = -0.04755232Nm \quad \text{(I.6)}$$

Due to lift being 0 (JavaFoil) or 0.152 (XFOIL) at 0degree AoA the setting angle should be set at a higher AoA so that lift can occur. A setting angle of 0, 5 and 10 will be calculated to find the ideal setting angle and pitching moment with corresponding CG location at 0.02m from the leading edge (LE).

Table 13 Pitching Moment about CG ($C_{M_{CG}}$)

Angle of Incidence (i)	XFOIL	JavaFoil
0	-0.04755232	-0.00008
5	-0.13531364	-0.18403523
10	-0.17841351	-0.27148424

From plotting $C_{M_{CG}}$ with varying CG locations it is possible to select the ideal static margin. The static margin should be defined as a range so that the aircraft design is computed for this range, as fuel decreases and the moments change the aircraft should be able to remain stable. As this is what is seen in larger aircraft this has been calculated but the as a CG between 0.02m and 0.03m from the LE. This calculation was completed using figures 30 and 31 to plot the CG change with both XFOIL and JavaFoil coefficient data ranges with an incidence angle of 0 degree AoA.



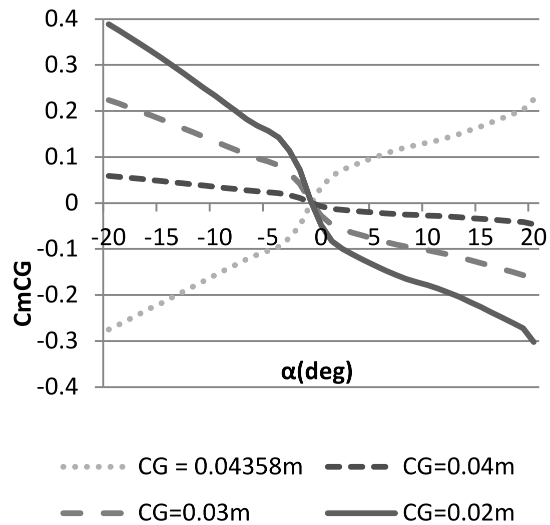


Figure 30 XFOIL Pitching Moment with CG change

Figure 31 JavaFoil Pitching Moment with CG change

The range is kept so that the longitudinal static stability is stable with a negative gradient for the pitching moment coefficient. As the simulation will have a point mass that is not variable a static margin should not be needed but a static margin can be computed so that stability tests can be performed within this region. Due to this region being very small the detail that the simulators need to be accurate too should be as high as possible.

Ideals

The optimum values for mass, power and velocities with the given coefficient data and wing geometry were found. These optimum values can be noted in table 14 using JavaFoil data, if using XFOIL data the incidence angle would have to be higher at an angle of 11 degree AoA (equation J.1).

$$L = 0.5 * \rho * v^2 * S * C_L = m * g$$
$$L = 0.5 * 1.225 * 6^2 * 0.00755 * C_L = 0.01 * 9.81$$
$$C_L = \frac{0.0981}{0.5*1.225*6^2*0.00755} = 0.5893 \text{ or above} \quad \text{(J.1)}$$

Table 14 Aircraft Optimum Flight Characteristics

Property	Script	Value
Mass	m	$0.01kg$
Stall Speed	V_{min}	$4.3m/s$
Cruise Sped	V_{cruise}	$6m/s$
Maximum Power	P	0.5W
Motor Efficiency	$Mot\eta$	50%
Propeller Efficiency	$Prop\eta$	80%
Incidence angle	i	5 deg
LE to CG	X_{CG}	0.02m
Pitching Moment about CG	$C_{M_{CG}}$	$-0.45544Nm$
Gradient of Pitching Moment Curve	$\frac{dC_m}{d\propto}$	-1.47039rad^{-1}

J. Simulation Models

Using the aircraft optimum flight characteristics that were calculated, the flight simulators could be programmed with all the relevant data needed. The data files for the Merlin, FlightGear and X-Plane models can be referred to in appendix 2.

Merlin

Step 1

The Cessna 172 model was edited to create the aircraft file with the MAV wing consisting of sizing and coefficient airfoil data. All Cessna 172 parts were removed except the fuselage, undercarriage and engine and altered accordingly to scale. The model also held a reduced fuselage, undercarriage and tailplane with effecting elevator as these could not be removed from the design.

The model was launched at 70kts and an altitude of 300ft. This modelling showed that the wing would fly with an apparent pitch oscillation and the CG change was very sensitive at this scale. To simulate at the original scale the inertia calculations for the simulated are not at a high enough detail. The scale factor used for this model was 1:10 as the weight had to be 100kg or above. When making scale changes it should be noted that the Reynolds number should also alter for input data required for the airfoil data gained from the CFD simulation software XFOIL and JavaFoil. This should also change for chord length changes when entering panel sections, this also highlights the need to model different reflex % for each panel section.

Step 2

Table 15 Merlin Stick Fixed Test Results

CG location from LE	0.15m	0.151m	0.152m	0.155m	0.173m	0.2m	0.3m
Trim Location	2NU	1NU	5ND	14ND	64ND	113ND	308ND
Response	Smaller continuous oscillations	Big oscillation that goes into a continuous small oscillations	Big oscillation that goes into a continuous medium oscillations	Large high frequency oscillations	Pitch up and continue to climb upside down	Pitch up and crashes program	Pitch up and crashes program

The tests for stick fixed neutral position was found by carrying out a series CG locations at a speed of 70knots at 300ft (table 15). The aircraft was loaded with a CG location of 0.2 due to the scale factor this was the equivalent of the 0.02m described in the previous calculations. This was not seen as the ideal location as the software loaded the aircraft with a pitch nose down of 113. To check that the calculations were correct and what increment of change was needed, the program was loaded with the aircraft CG location of 0.3m. From this the software showed that the calculations were correct and that the aircraft would have to load at a larger nose down position and would become more unstable which it did. The software was then reloaded with a CG location of 0.173 as a starting position. This flight location flew well with a launch speed of 70knots but had an unusual flying pattern. This effect involves the wing increasing in pitch until it is fully inverted where it continues to fly inverted in a stable manor and climbs with altitude (figure 32 and 33).

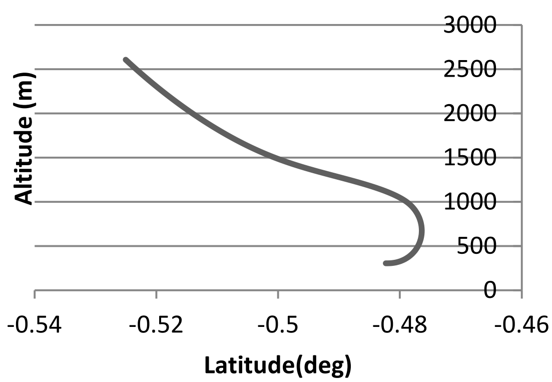


Figure 32 Merlin Phase 1 Altitude vs. Latitude (CG 0.173)

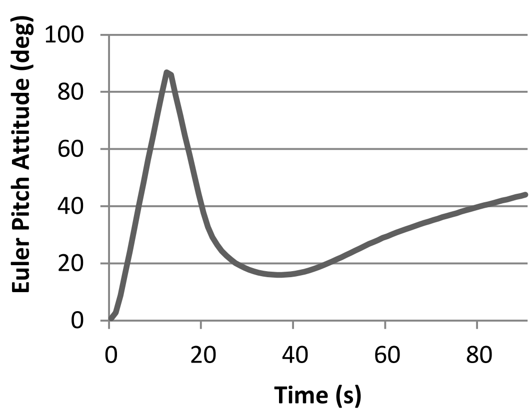


Figure 33 Merlin Phase 1 Euler Pitch Attitude(CG 0.173)

Figure 32 shows longitude vs. altitude giving a clear representation of the movement as it gains altitude. The angle at which the airframe moves and changes can be measured in by Euler Pitch Attitude this can also be seen in figure 33.

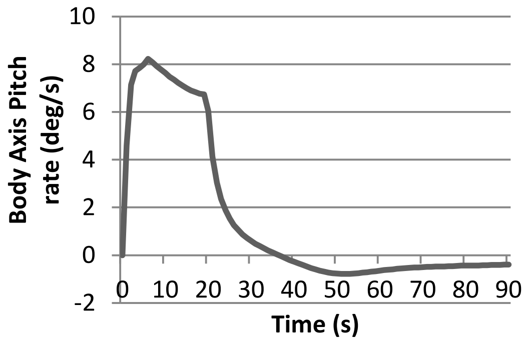


Figure 34 Merlin Phase 1 Body Axis Pitch Rate (CG 0.173)

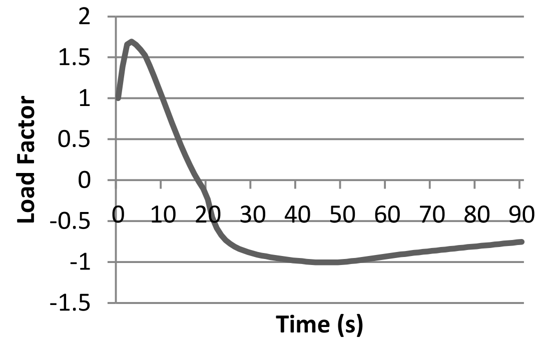


Figure 35 Merlin Phase 1 Load Factor(CG 0.173)

Body Axis Pitch Rate (figure 34) shows the rate at which it moves per second from this the Body Axis Pitch Acceleration can be calculated. This shows that at the initial phase of t = 0 - 5s there is acceleration and at t = 20s deceleration takes place. When comparing this to figure 33 plotting Euler Pitch Attitude it is clear that the change in acceleration is due to the change in angle of attack. This change will result in a change the data being read in the look up table for how much lift, drag and pitching moment is being produced. This means that the effect and movement is being created due to the numbers in the look up table therefore an aerodynamic behaviour and not an error in other input parameters. Also at t = 20s the Load Factor (Lift to Drag Ratio) reaches 0 and then becomes negative as the aircraft becomes inverted, this can be seen when comparing figures 32 and 35. Although the Load Factor is negative therefore the aircraft is inverted from t = 20 - 90s the wing increases in attitude (Figure 32) proving that the aircraft can continue to produce lift whilst in an inverted flight condition. This inverted flight pattern is not ideal; to counteract the rotation the CG location must be moved forward as stated by the calculations from the airfoil data results.

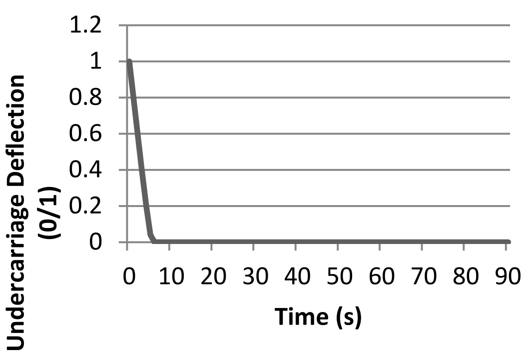


Figure 36 Merlin Undercarriage Deflection (CG 0.173)

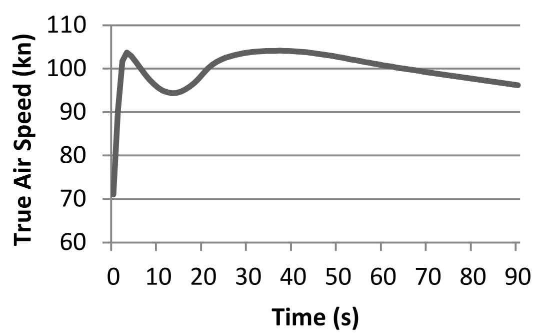


Figure 37 Merlin true Air Speed (CG 0.173)

The initial pitch that occurs between 0 and 8 seconds could be directly related to the undercarriage deflection as it changes from the extended position to the retracted position. This primary oscillation is not ideal and changes the flight data accordingly. As the undercarriage data should be viewed as negligible no affect should occur whilst modelling as this will alter the data as seen with a pitch oscillation. This error should be removed before testing can be continued.

Another noticeable effect is that the aircraft becomes stable whilst in the inverted position. This could be due to the ideal CG location for the inverted aircraft is the 0.173m. At the point whilst inverted the aircraft becomes stable at a higher speed of 100knots full throttle. The true air speed recorded is that of what should be expected with an increase as the aircraft pitches up and loss of speed whilst the aircraft rotates from the vertical to the inverted position, then becoming constant whilst travelling inverted as lift is still being produced. From this test there seems to be no effect in roll and the aircraft has lateral stability (figure 38).

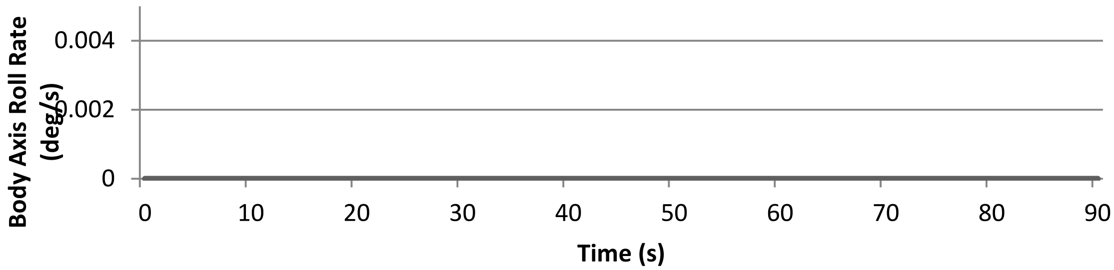


Figure 38 Merlin Body Axis roll rate (CG 0.173)

Following the 0.173m test the CG location was moved further forward to 0.155m (figure 39) at this point the aircraft incurred a large high frequency pitch response with a period roughly of that of the time taken to retract the landing gear which had the same response and time characteristics of those seen in the test for the CG location of 0.173m. The oscillation shows a high amplitude and short period response with a low frequency carrier wave. This response does not reduce and is continuous, leading to the need for a PID feedback loop controller to settle the pitch amplitude.

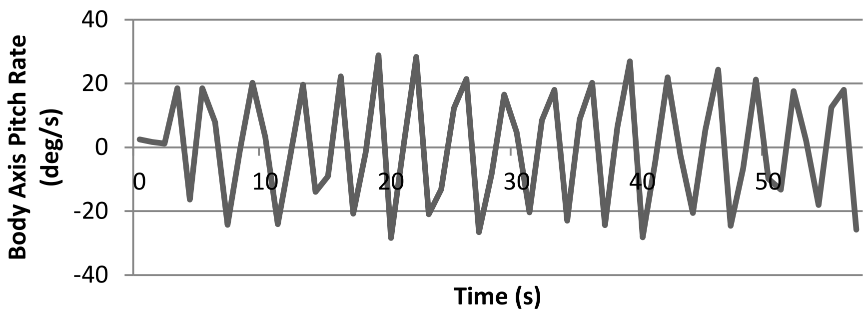
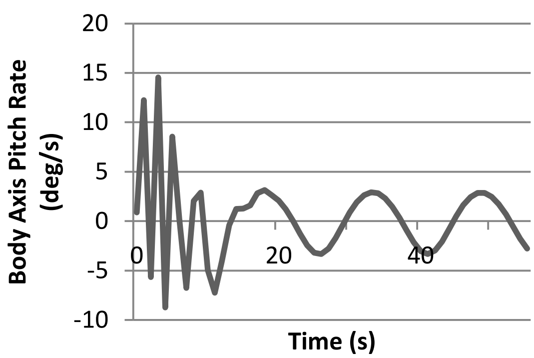


Figure 39 Merlin Body Axis Pitch Rate (CG 0.155)

Moving the CG location further forward the response alters as seen in figure 40 and 41. The response seen with a CG location of 0.155m is seen in the first few seconds but reduces in amplitude and a low frequency response is seen that again is continuous. However it is noted that the initial response is reduced quicker with the CG location at 0.151m, closer to the leading edge.



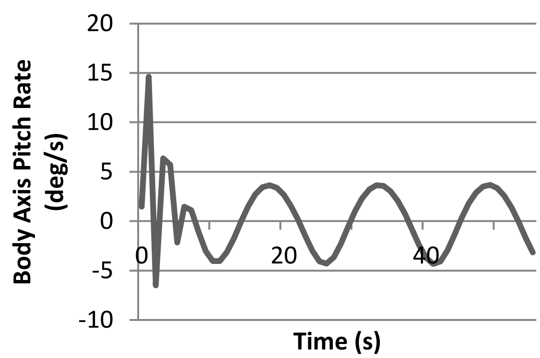


Figure 40Merlin Body Axis Pitch Rate (CG 0.152) **Figure 41Merlin Body Axis Pitch Rate (CG 0.151)**

Other than the retracting undercarriage error the thrust from to the engine initially starts at zero which could lead to another pitch frequency response which could be the reason for two frequency pitch responses seen in figure 40 and 41.

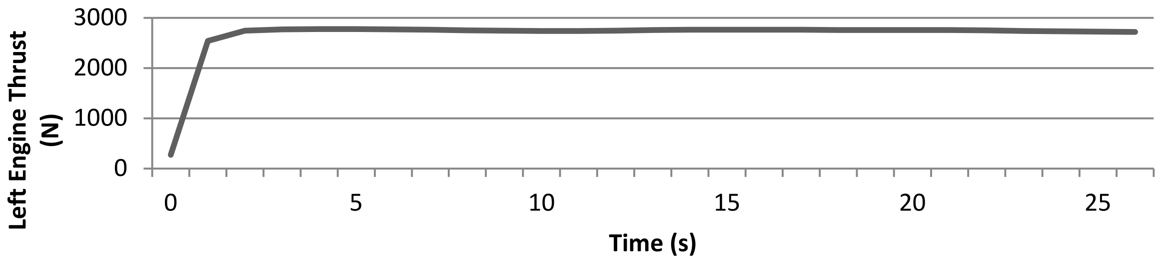


Figure 42 Merlin Thrust (CG 0.151)

Another important finding is the altitude and true airspeed response seen from CG location of 0.155m to 0.151m. With all tests the aircraft seems to increase in altitude relatively quickly due to the high lift produced from the wing. There is a slight oscillation that occurs from the pitch oscillation as well as the air speed oscillation (figure 43 and 44). The air speed oscillation dampens quicker in the CG location of 0.155m than that of the CG location of 0.151m (figure 46). Because of this there is a lower frequency and amplitude oscillation seen in the increasing altitude with the CG location further back than that of 0.151m. This occurrence may mean that the CG location is not ideally at 0.151m but further forward and that a feedback controller may have to be used to remove the oscillation that occurs from the retracting undercarriage.

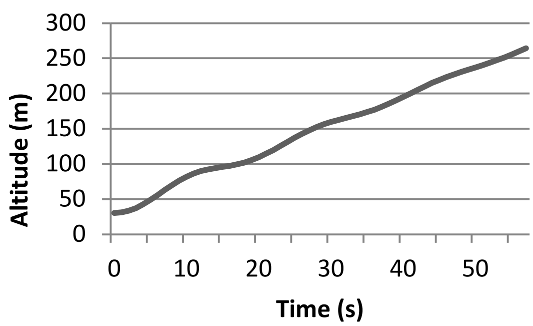


Figure 43 Merlin Altitude (CG 0.155)

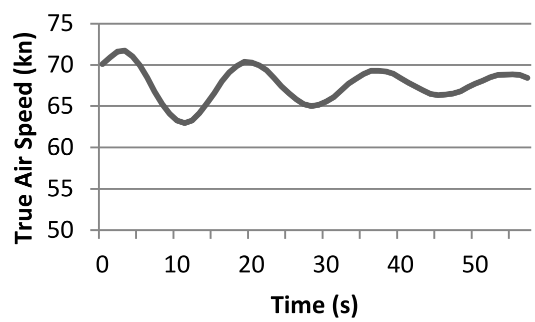


Figure 44 Merlin True Air Speed (CG 0.155)

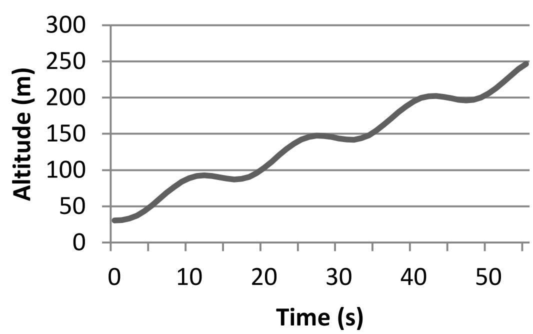


Figure 45 Merlin Altitude (CG 0.151)

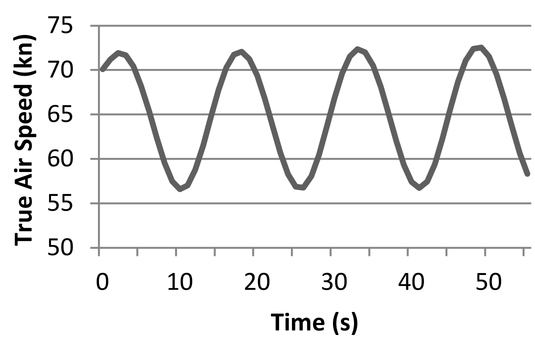


Figure 46 Merlin True Air Speed (CG 0.151)

Due to the undercarriage deflection on launch further tests could not be completed until the matter was resolved, however this was not completed. Further tests would have been carried out to find the stick free neutral position by loading the model at varying speeds between 50 and 100knots and measuring the longitudinal stick position output. This would be measured between 1 and -1. This would then have found the ideal flight speed for this model.

Step 3, 4, 5 and 6

Concluding this, the longitudinal tests such as velocity input, elevator deflection and wind gust tests could have been performed. The velocity tests would have been controlled via the loading panel and loading at the required speed of 100knots and sharply changing the throttle control. The same would have been repeated for elevator deflection. Due to the unstable flight pattern seen from step 2 any further tests were not completed. If step three were to be performed the stick location could be recorded from a range from -1 to 1 and supplemented for stick force. The step input test would have been performed by a movement on the throttle control and recorded as throttle position or thrust output. The elevator deflection again would be recorded by stick position and results analysed as previously recorded. The wind gust test could not have been recorded as only heading wind direction and speed could be chosen and no vertical gusts apart from turbulence could be created.

FlightGear

This model was input in the correct scale and engines and propeller were left as they were with the original model to the scale being correct. The elevator was simulated as a portion of the tailplane at which was located at the rear of the wing section along with the aileron control tabs.

Step 1

Keeping the flight simulators in the most similar testing conditions the altitude was chosen to be 300ft. When loading the model at low speeds such as 10knots the aircraft increased its speed too roughly 55knots where the speed remained constant at a throttle position of 0.5. Because of this the tests were started at a speed of 40knots to account for the fluctuation of speed at the beginning of the test flights.

Step 2

Four major tests were completed and were of similar values to that taken for Merlin and the predicted stability CG location. These can be clearly noted in table 16 along with a summary of the findings. It should be noted is that trim is not stated on the instrument panel or HUD in this flight simulator and therefore the Trim location is an estimate of what the trim should be. Elevator trim out is externally analysed as a property (/controls/flight/elevator-trim) and an initial elevator trim location could be set within JSBSim-set.xml.

Table 16 Flight Gear Stick Fixed Test Results

CG location from LE	0.01m	0.015m	0.02m	0.03m
Trim Location	40ND	20ND	10ND	10NU
Response	Pitch down oscillation but climbs in altitude	Pitch down, oscillation and crashes	Pitch up and Climbs in altitude	Pitch down and crash land
Pitch oscillation range	+17 to -4	+25 to -6	+24 to -11	+8 to -6

The aileron trim tab was set to 0.25 for counteracting the torque of the propeller but this was not consistent. When altering the trim tab position, the simulation would be reloaded and would have the same effect however when running the simulation and restarting in the simulation would change the roll movement. This roll movement is clearly visible in all test flights and should be resolved with further research (figure 47).

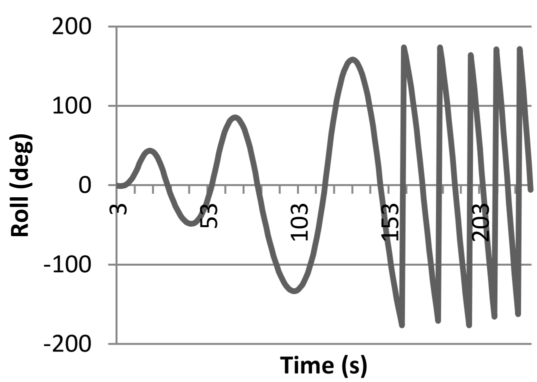


Figure 47 FlightGear Roll (deg) (CG 0.02)

With all pitch responses there is an initial oscillation that moves into a large response, this could be to do with the initial fluctuation of airspeed. This then either dampens quickly as seen with the location of 0.02m from the

LE or does not get a chance to dampen with 0.03m from the LE as the aircraft hits the ground. The oscillations dampen slightly slower the nearer the leading edge as seen in figure 48.

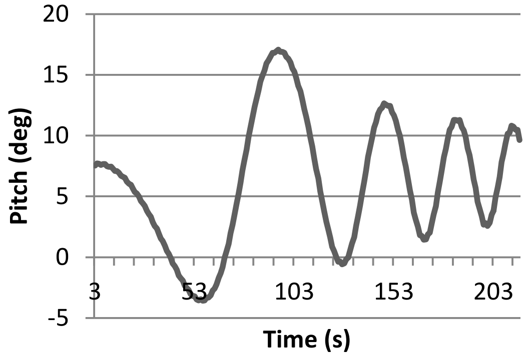


Figure 48 FlightGear Pitch (deg) (CG 0.01)

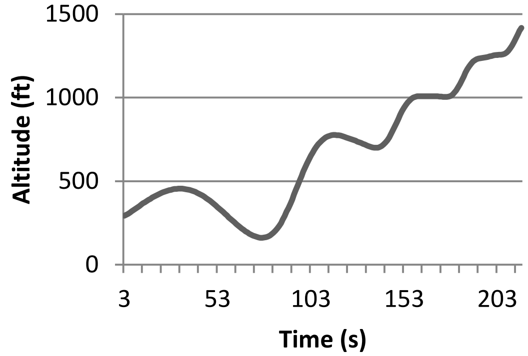


Figure 49 FlightGear Altitude (ft) (CG 0.01)

Both 0.015m and 0.03m tests result in a crash landing this is due to the large oscillations in pitch affecting the altitude or the CG being too far back and pitches down and crashes. For 0.01m the altitude oscillations reduces with the pitch oscillations as the pitch oscillation reduces quicker with 0.02m the altitude oscillation dampens also quicker (figure 49).

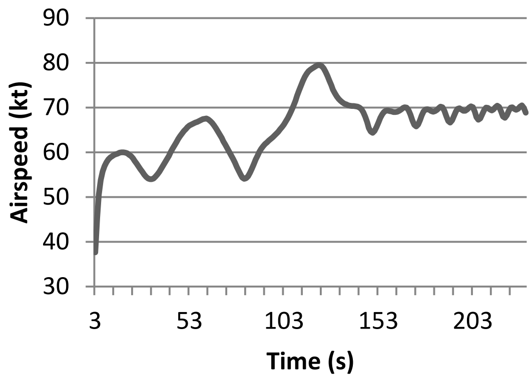


Figure 50 FlightGear Airspeed (kt) (CG 0.02)

The airspeed steadily increases with an induced oscillation from the pitch oscillation with a lag of 180 degrees. This can be seen in figure 50 for the CG location of 0.02 and also in all CG location tests. What is apparent to all is that the airspeed tends toward 70knots, being slightly larger for the CG location nearer the LE. Overall the most stable positioning seemed to be the predicted 0.02 CG location because of the reduced pitch oscillations and the nose up attitude. This position will then be used for the longitudinal stability tests with velocity and pitch for steps four and five.

Step 3

Due to the stick force could not be outputted by FlightGear this step was not completed.

Step 4

Because of the roll instabilities shown previously, a step input velocity was taken for CG location 0.02 but the results are not conclusive as they were not taken in a straight and level flight condition. Initially what should be noted is that the airspeed increased from the initial 40knots to roughly 50knots without any input, after this had settled the velocity input was performed at 21seconds and the airspeed fluctuated from 58 to 50 knots that damped very slowly as the first period took 30 seconds and then the second 20 seconds (figure51). This showed that the oscillation needs to be damped and that the oscillation would reduce naturally if left un-dampened. The fluctuating airspeed also directly affects the altitude as there was an immediate reduction in climb and the oscillations of airspeed are directly proportionate to the altitude oscillations (figure 52).

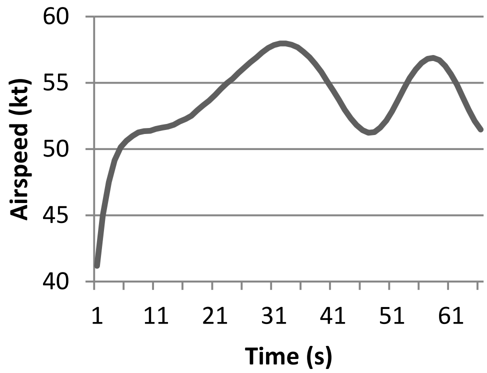


Figure 51 FlightGear input Velocity, Airspeed (kt) (CG 0.02)

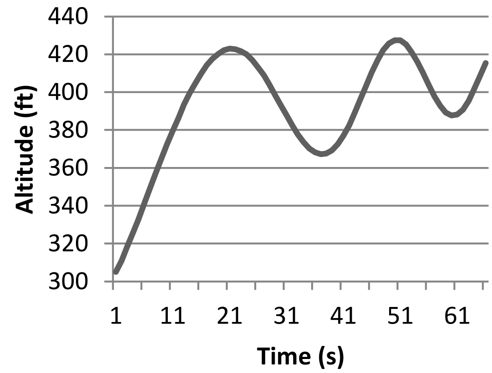


Figure 52 FlightGear Input Velocity, Altitude (ft) (CG 0.02)

It should also be noted that there is a constant pitch oscillation of low amplitude and short period with a low frequency carrier wave as that also seen with the outputs by the Merlin flight simulators (figure53). The effect of the velocity input actually decreases the amplitude of the pitch oscillation showing that the initial oscillation is due to the fluctuating loading speed.

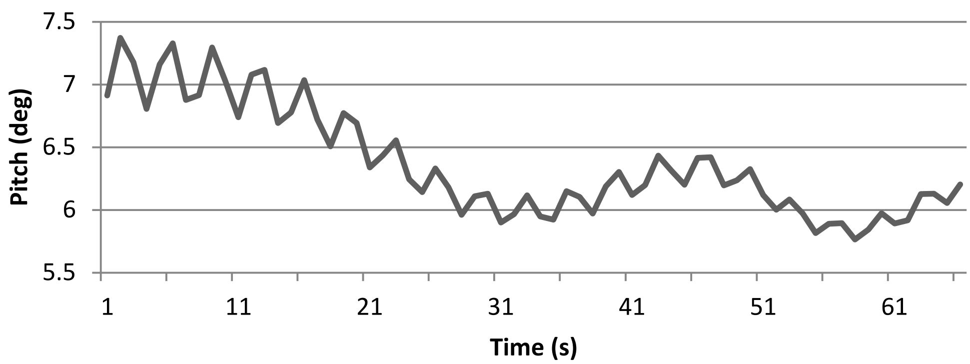


Figure 53 FlightGear Input Velocity, Pitch (deg) (CG 0.02)

Step 5

The longitudinal step input of pitch was also recorded; this was completed by loading the model under the same conditions and waiting until the airspeed was constant, a few seconds later a pitch input was performed and the following results were shown. The pitch input increases the amplitude of the original oscillation and dampens somewhat quickly back to the original amplitude. This is good and does not oscillate uncontrollably. This response is good however the original oscillation should be removed and the test should be repeated at a stable straight and level flying condition.

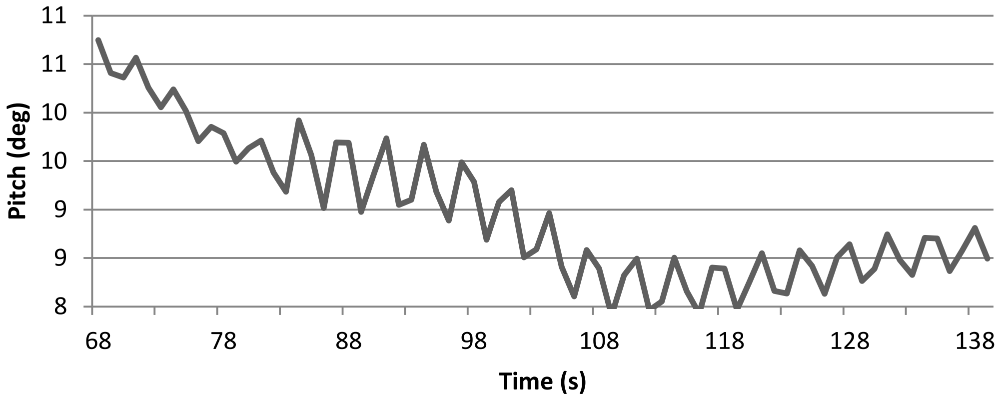
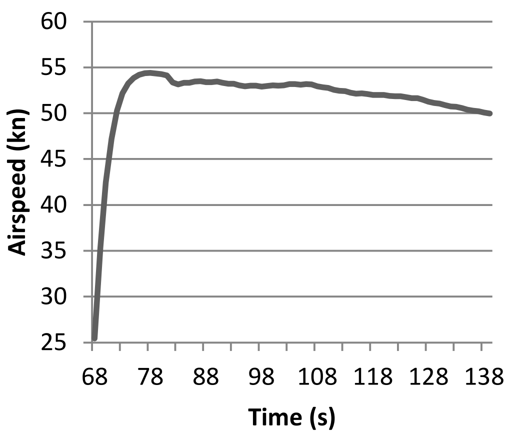


Figure 54 FlightGear Input Pitch, Pitch (deg) (CG 0.02)

The pitch input was quick and seems excite the pitch oscilation, there is a slight decrease in speed that is constant and shows no correlated oscillation (figure 55) and this does not affect the climb rate which is steady and constant (figure 56). The roll rate was also not affected travelling at the same rate as seen in previous tests.



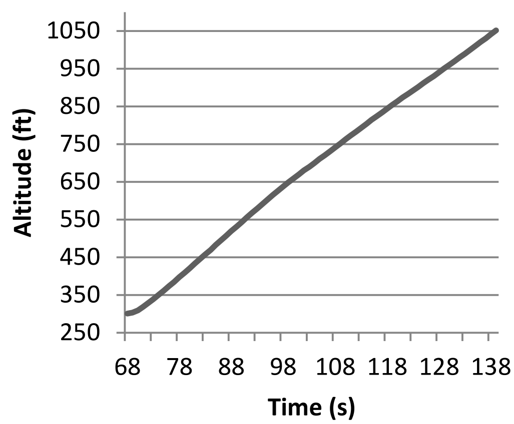


Figure 55 FlightGear Input Pitch, Airspeed (kt) (CG 0.02)

Figure 56 FlightGear Input Pitch, Altitude (ft) (CG 0.02)

Step 6

The wing gust tests were not taken as the flight simulator again like Merlin could only simulate horizontal wind gusts from a heading direction, however the detail of different weather condition at various altitudes could be performed which is more detailed the Merlin flight simulator.

X-Plane

The model created in X-Plane is to scale and had the original engine and propeller used from the original model with a reduced prop size and brake horse power. The elevator and aileron were modelled as a section on the wing.

Step 1

Like the previous models the aircraft was loaded at 300ft with an initial speed of 70knots. This however may not be the ideal loading condition but when this was altered no changes were apparent.

Step 2

The MAV was first simulated in the required conditions of CG location 0.02 from the leading edge but the propeller failed to be responsive and the roll rate was excessive compared to the fluctuating pitch response. What should be noted was that the trust output (figure 57) would start at as negative and the elevator (figure 58) would become negative, when the thrust increased and became positive the elevator also reverted to the positive position. The lift to drag ratio highlighted that also the drag is high this may be a result for the undercarriage or due to the aircraft excessive rolling and loss in altitude.

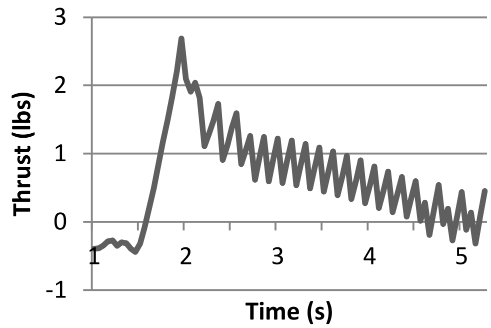


Figure 57 X-Plane Test A; Thrust (lbs)

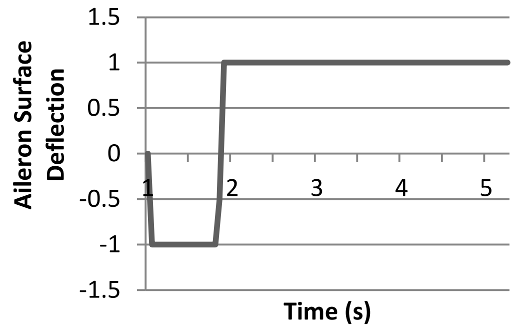


Figure 58 X-Plane Test A; Aileron Surface Deflection

To overcome the roll several steps were taken to reduce the roll rate;

A. Increasing the reference speed for the roll force to 100knots
B. Changing the aileron deflection to 35% and 15% to produce a trim factor
C. Roll damping of 10, 20 and 40 lb/(deg/s)
D. Removed elevator and aileron
E. Alter wing incidence angle
F. Altering the BHP and engine specs

From completing these changes the following was noted; increasing the reference speed for the roll force did not affect the roll rate (figure 59).

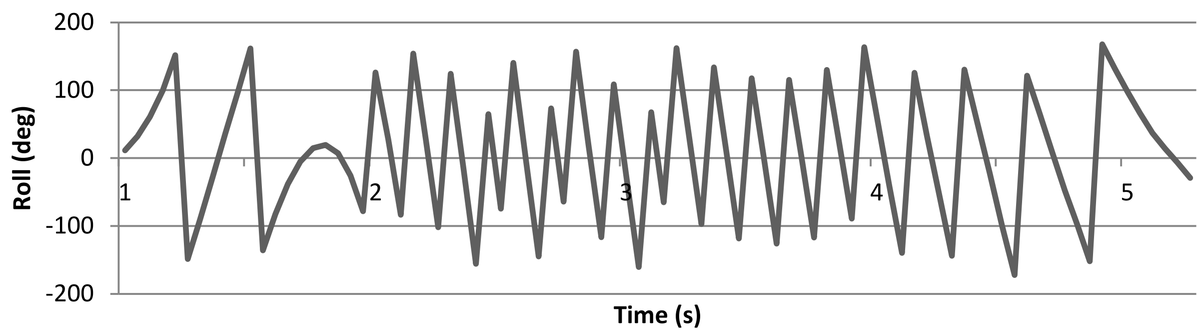
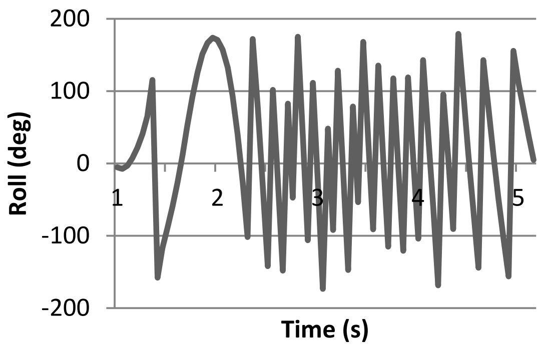


Figure 59 X-Plane Test A; Roll (deg)

Changing the aileron deflection initially keeps the aircraft level with a rotating opposing motion however this is overcome by the initial roll property (figure 60). Because of this the initial response to the roll is much slower but regains its original roll pattern. It should also be noted that this change also affects the initial thrust increase as it slows and becomes more erratic.



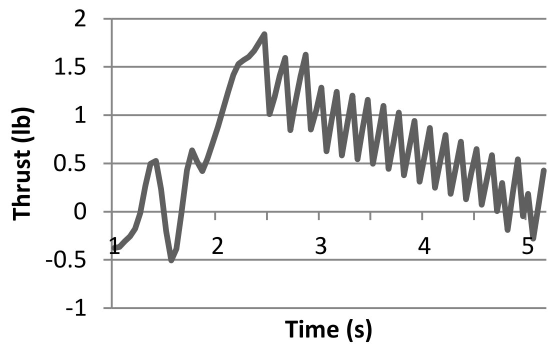


Figure 60 X-Plane Test B; Roll (deg)

Figure 61 X-Plane Test B; Thrust (lb)

By increasing the roll damping to 20lb (deg/s) shows that the response tends to be similar to the FlightGear output, initially moving slowly into a roll pattern that is affected by the pitch. With a lower or higher roll damping the roll becomes more unpredictable. With 20lb (deg/s) of roll damping the roll rate is reduced by a small factor but not enough to remove the rolling action.

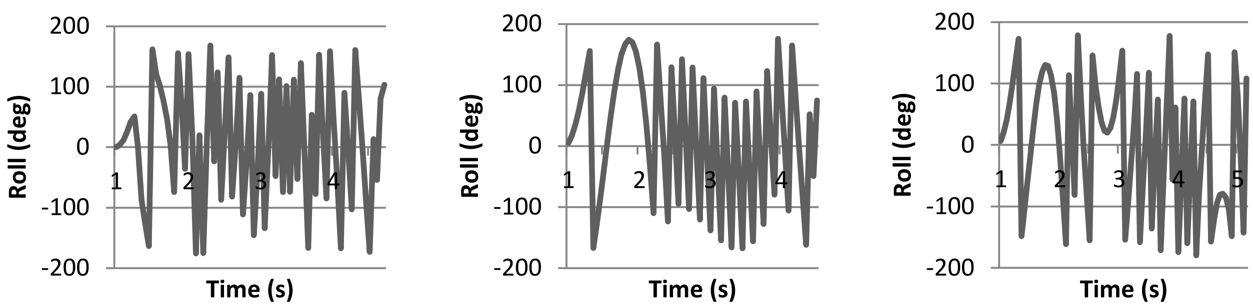


Figure 62 X-Plane Test C; Damping for 1=10 lb/(deg/s), 2= 20 lb/(deg/s), 3=40 lb/(deg/s)

By removing the elevator and aileron from the wing section the roll feature still take place. Therefore for the sake of further testing steps requiring elevators the elevators were left for further testing.

By altering the wing incidence angle the wing tips would curve back to the original position like wing tips, this is not the intended positioning but is a good design feature to model winglets. Altering the BHP and length of the prop had little effect, decreasing the prop diameter reduced the rotation rate and increases the spin speed of the prop but this did not affect the roll rate.

After all these processes had been taken to reduce the roll rate with no resolution the testing was started with varying CG locations (table 17).

Table 17 X-Plane Stick Fixed Test Results

CG location from LE	0.019m	0.022m	0.028m
Trim Location	-	-	-
Response	Pitch oscillations mainly positive with lower roll rate with better constant thrust.	Erratic roll and aileron deflection, pitch tries to tend positive	Negative high pitch oscillations with high roll rate and erratic thrust condition

The recoded pitch was of that expected from results found by Merlin and FlightGear showing that the pitch response to be positive for 0.019m reducing to a negative response for 0.028m as the CG location is located too far back. The roll rate is reduced with the increase in pitch and CG location being moved further forward toward to LE (figure 64).

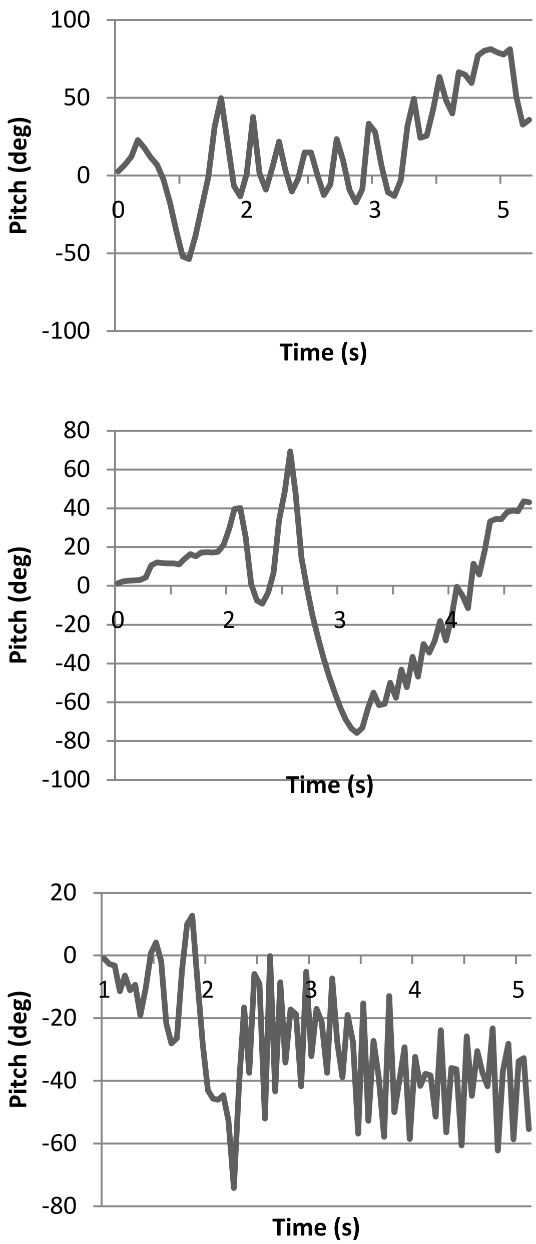


Figure 63 X-Plane CG Test; Pitch (deg) for CG = 0.019m, CG = 0.022m and CG= 0.028m

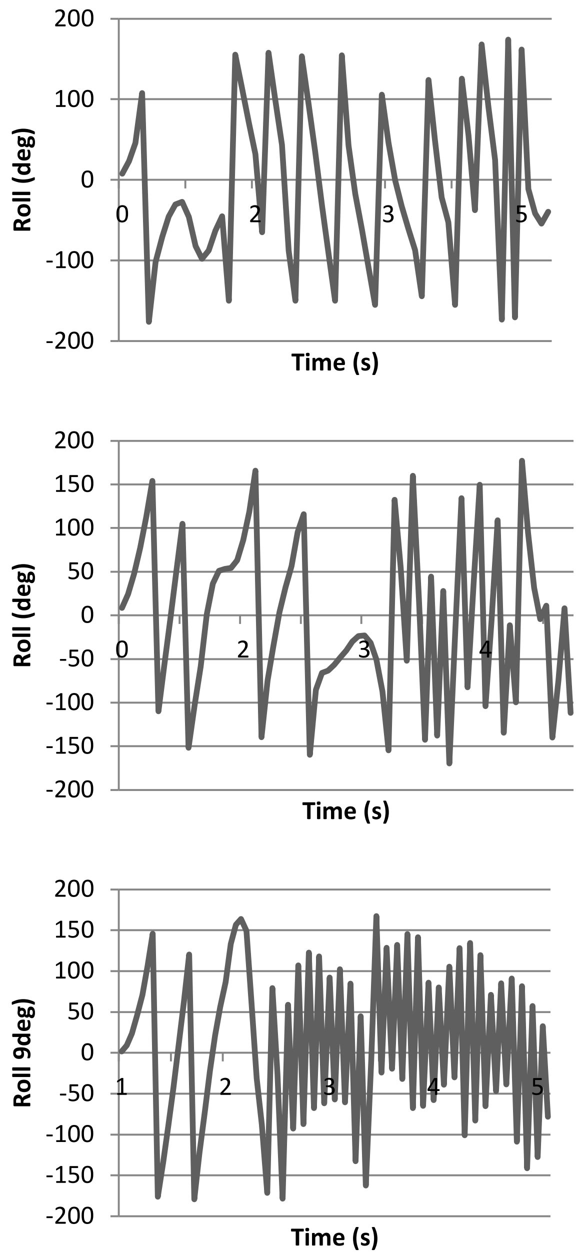


Figure 64 X-Plane CG Test; Roll (deg) for CG = 0.019m, CG = 0.022m and CG= 0.028m

The aileron control surface starts centred and due to the initial 1.6 second irrational behaviour the aileron moves to the negative location then changes to the positive location. With 0.019m and 0.028m locations this is true but with 0.022m location the aileron moves to the negative position and then again moves to the negative location before moving to the positive location at 3.3 seconds. The initial thought was that the roll was being affected by the aileron movement but the aileron movement seems to be a side effect of the roll effect. This could be seen in the visual pan shot and could be replayed whilst looking at the analysis section of the simulator.

The thrust initially starts at 0 and increases to 5lbs of thrust at 1.5 seconds for CG locations 0.019m and 0.028m. With 0.028m location the thrust reaches 2lbs at 2 seconds and overshoots and fluctuates between 2 and 1lb, whereas with the other two locations it remains constant with slight fluctuations with 0.022m location. The lift to drag ratio for these tests is low with lower lift to drag ratio for the location being further back from the LE, this is assumed to occur due to the increased roll rate and the negative pitch due to the CG positioning.

From these results it was noted that the ideal location from these tests was 0.019m CG location. This was due to the higher lift to drag ratio caused by the reduced roll and pitch rate, with the pitch tending to increase and the thrust being more constant.

What should also be noted is the prop was stalled throughout the testing so the prop was still spinning but not creating sufficient thrust which would produce a small torque from the propeller. Without thrust the wing is performing a glide not powered flight compared to the other simulated results and the tests could not be performed without an engine installed.

Step 3, 4, 5 and 6

Step three could not be performed due to stick forces not being recorded in X-Plane, this could be replaced by aileron, rudder and elevator joystick values ranging from -1 to 1 however it was noted that the elevator input was 1 to 0 to 1 from nose down, centred to nose up positions. With this noted the tests would have to be scribed to note the elevator positioning.

The input velocity test would be performed with the movement of the throttle positioning on the joystick and elevator deflection as described above with joystick movements. The velocity output data would be recorded by thrust (_thrst,_1,lb), elevator deflection (_elev,_surf) and elevator joystick position (_elev,yoke1).

The test for a wind gust input could not be performed as again the vertical gust could not be modelled however the complexity of this simulation allows layers of weather conditions to be created and three horizontal wind gust layers of alternate direction and speed could be simulated and also turbulence.

K. Simulator Feasibility Study

For results please see appendix 3 on page 66. The study was completed by the author of this project only.

V. Discussion

L. Coefficient Data Models and Software

The main findings that were produced from both XFOIL and JavaFoil were the coefficient data. Upon initial investigation the results were highly similar and only slight differences occurred. These included the higher overall drag by JavaFoil and the loss of lift effect at 8 degrees not visible in the XFOIL data. The major difference was the pitching moment and that the XFOIL data was taken about the Trailing Edge (TE) which could not be used to model the ideal CG location. If there were more time to research into using this software and altering the pitching moment reference point this program could have been used by the simulators for analysis. Because of this JavaFoil results were used and the simulators did not have to be reprogrammed with both airfoil coefficient data. Looking back to the initial intensions of the report the user has to be particularly aware of the setup details within XFoil.

Using data taken from simulated research provided by Coventry University staff on this wing design, analysis on the accuracy of the data can be made to prove if the simulations were close to that expected and to judge this against the software being used. The researched data was provided in CFD simulation software OpenFoam from Open CFD software. These results are for a 1 second time frame range at a rate of 0.00001s intervals. This included time dependent velocity and pressure distribution and coefficients of lift drag and pitching moment at zero, five and ten degree AoA.

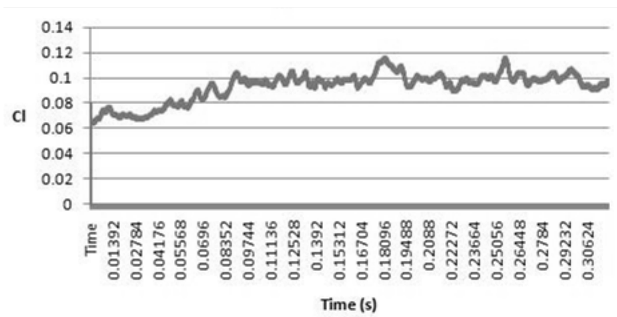


Figure 65 OpenFoam, Time Dependent Lift at 0α

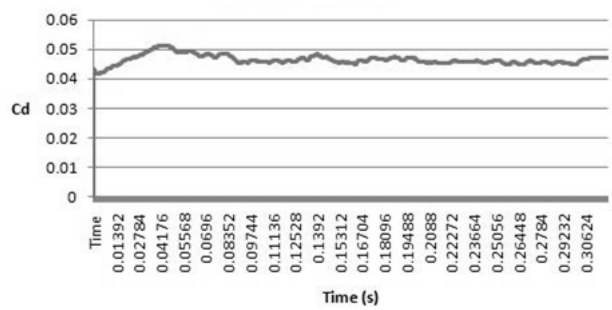


Figure 66 OpenFoam, Time Dependent Drag at 0α

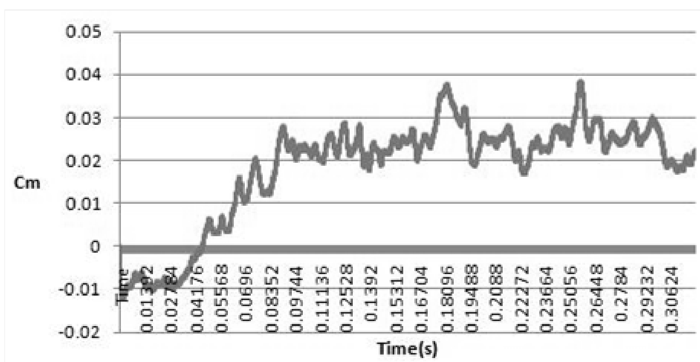


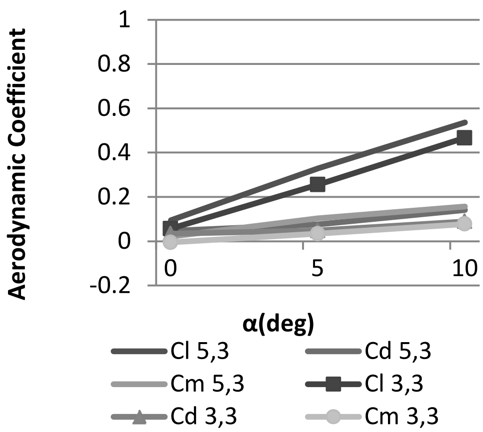
Figure 67 OpenFoam, Time Dependent Pitching Moment at 0α.

As seen in figure 65, 66 and 67, there are dominant high and low frequency oscillations to the results this is due to the airflow circulation under the first camber seen in figure 1 and 2. Data was also produced of the MAV wing with the same dimensions with a change in camber percentage (3%, 3% double camber). The following graphs show the coefficient results of one second of both models. They also show that of the two models produced the 5, 3 wing has an increased lift, drag and pitching moment. If the data were to be used in the flight simulation software the range of AOA values would have to be increased, depending on the flight simulator programs. To model the frequency oscillations a detailed feedback loop could be used to model the first second of flight the oscillations within that second then could be expanded throughout the simulation. Due to the accuracy of the data modelled the detail would be lost in the flight simulators as the frame rate is too slow as seen in table 18. From assessing the time dependant moment coefficient it shows a very quick input at the start of the initial flight that is also seen when loading the aircraft in flight although this input is much smaller and faster the response input is the same to that seen in the flight simulators.

Table 18 Flight Simulator Frame Rates

Flight Simulator	Frame Rate (f/s)
Merlin	1
FlightGear	8
X-Plane	15

Analysing the graphs seen by Null and Shkarayev (2005) with those done in the CFD program the results are similar to what should be expected (figure 68 and 69). It must be stated that the results should differ as it has a slightly lower camber and higher Reynolds Number in the results for the model seen in this project but these are the results closest to that in this project. What would make the comparison more accurate would be to have a larger angle of attack range with more detail as only 0, 5 and 10 degrees were computed. Only the limited range of results shown, were available when this project was completed.



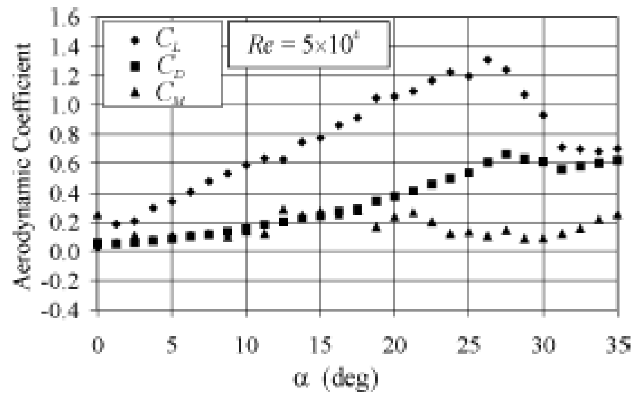
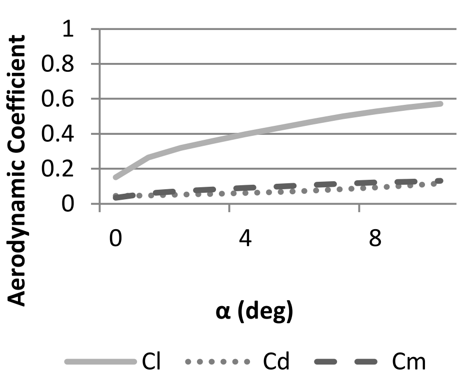


Figure 68 OpenFoam, 5,3% and 3,3% camber at Re = 6x10^4 Aerodynamic Coefficients

Figure 69 Null and Shkarayev, 6% camber at Re = 5x10^4 Aerodynamic Coefficients

Null and Shkarayev's (2005) results seen in figure 69 are highly similar to the results for this projects findings (figures 21 and 22) model for example the coefficient of lift was slightly lower at 0.1, 0.3 and 0.5 to that of 0.2, 0.4 and 0.6 at 0, 5 and 10 degrees AOA. Coefficient of drag however was highly similar at 0.05, 0.07 and 0.13 to figure 69. However this shows that the model has a lower lift and higher drag so lower lift to drag ratio. Coefficient of pitching moment is also highly similar which shows a neutrally stable design, although of the results given by the CFD model it shows the aircraft as unstable due to the positive gradient which needs to be resolved to create a stable aircraft. The comparison of CFD data to the XFOIL is highly similar however JavaFoil has over predicted the amount of lift that can be produced. For this reason statistically XFOIL data is more accurate including lift drag and pitching moments (Figures 70 and 71).



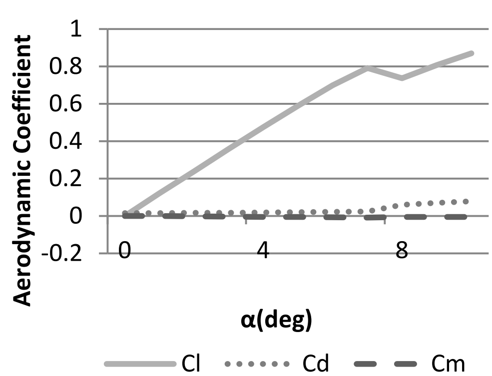


Figure 70 XFOIL Aerodynamic Coefficients (α=0^o to 10^o)

Figure 71 JavaFoil Aerodynamic Coefficients (α=0^o to 10^o)

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Figure 72 Stanford et al. (2008) Coefficient of Lift and Drag for model seen

Data can also be compared to that of a similar aspect ratio model with a reverse camber that is of a smaller camber and percentage. Theory explained previously showed that with a smaller reverse camber the lift should be higher as there is a higher percentage of cambered for the wing. The results seen by Stanford et al. (2008) also prove this and are highly similar to the results found for this projects model with the slight reduction in lift (figure 72).

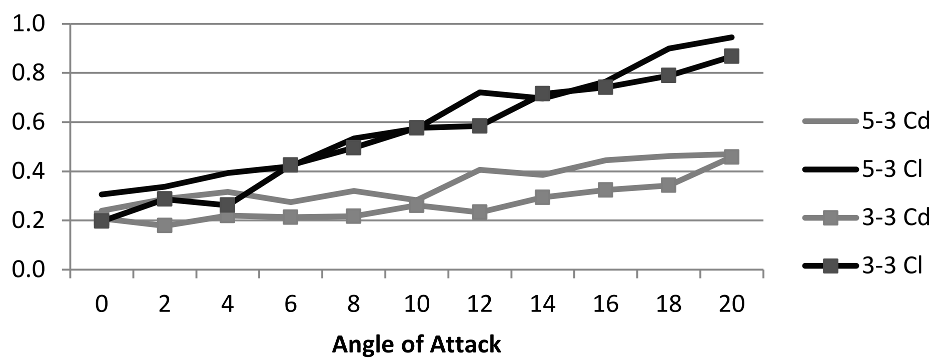

Figure 73 Wind Tunnel Results (Velocity = 5m/s)

Wind tunnel data was also taken for the wing at Coventry University and results were to be highly similar to XFOIL and CFD data although slightly lower than those outputted by JavaFoil (Figure 73). Testing errors such as air temperature or calibration errors should be noted however minimal when comparing these results.

There are no apparent anomalies to the results but the results need to be with a wider more detailed range of results and less dependent on time as the flight simulators are not detailed enough to simulate time dependant coefficient variables.

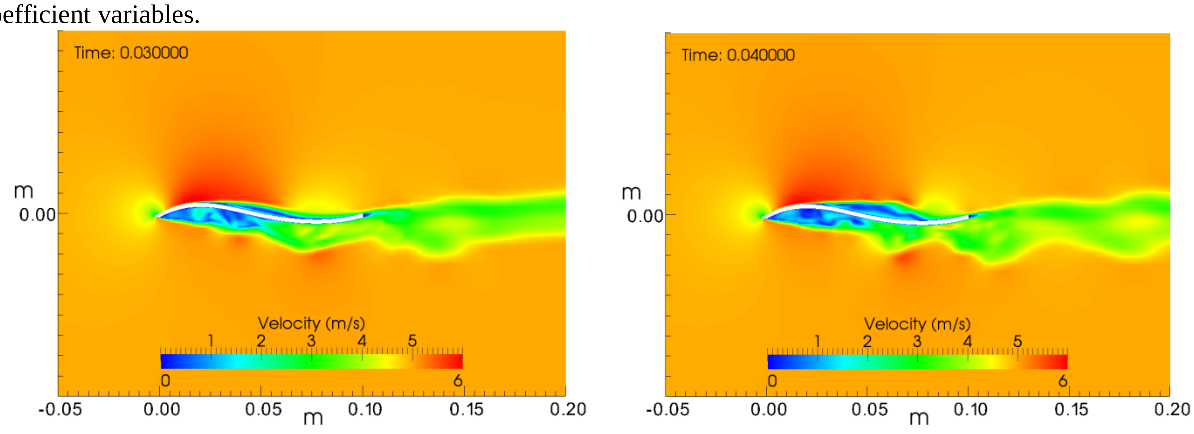

Figure 74 OpenFoam, Velocity at t = 0.003s and t = 0.004s

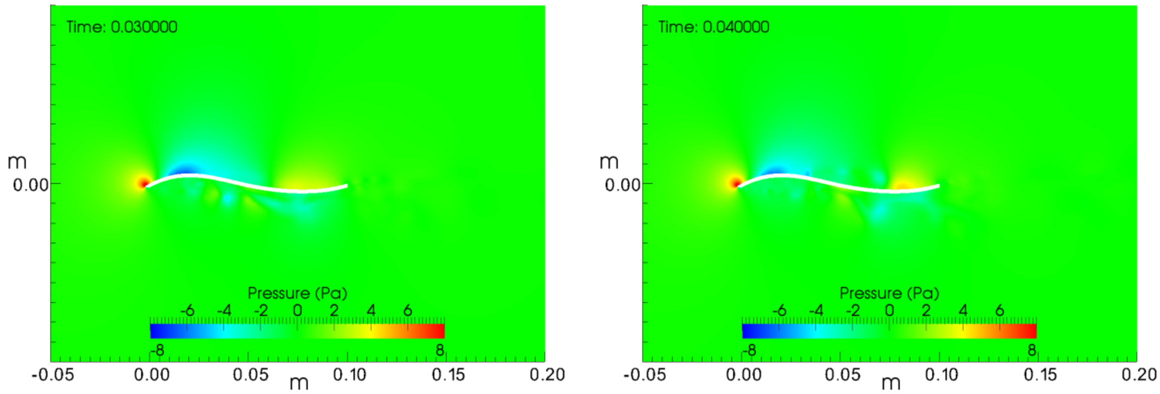

Figure 75 OpenFoam, Pressure at t = 0.003s and t = 0.004s

Figure 74 created by the CFD analysis by Coventry Universities parallel project shows the formation of separation bubble generated in the lower section of the wing at zero AOA; it can also be seen in figure 75 showing the pressure around the wing. This separation bubble gives rise to a region of low pressure as it travels downstream along the length of the wing. However the boundary layer stabilizes and the separation bubble dissipates at t = 0.036s. This separation bubble could cause the wing to initially increase in pitch the decrease in pitch as the pressure bubble moves along the wing which is seen in the flight simulation findings. This could cause an unusual pitching flight trait and should be researched further. The tests could be performed with an increasing velocity as ideally the aircraft would be hand launched. With this type of analysis the results would not be suitable for current flight simulators. The OpenFoam simulation also shows the development of wing tip vortices and the need for winglets or wing tip development to reduce the disrupting airflow moving over the wing disrupting the lift this may also affect the flight characteristics of the wing that were seen in the flight simulation with disturbances in roll (figure 76).

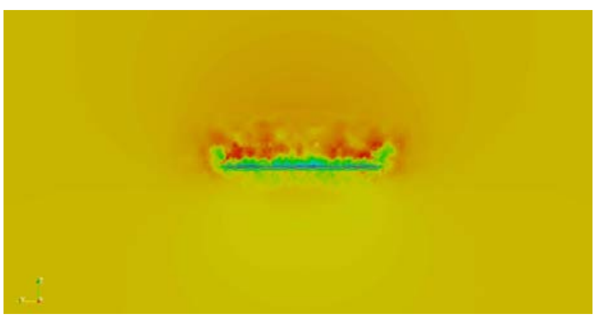

Figure 76 Development of Tip Vortices created in OpenFoam

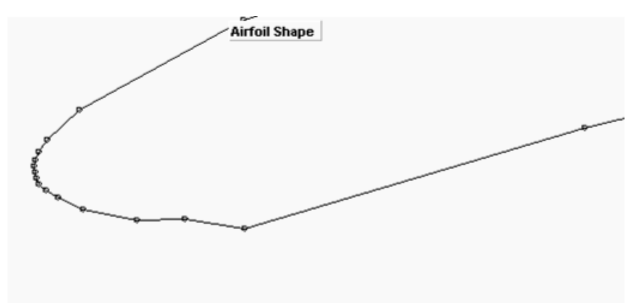

Figure 77 JavaFoil Airfoil Detail

When the simulation was carried out in JavaFoil an error in the wing design was noticed showing one leading edge point that was too low, causing an incorrect sharp edge (Figure 75). This matter was not resolved throughout this report or that seen in the OpenFoam modelling but future work should resolve this issue in future design developments for this model.

Summarising the software usability JavaFoil is the quickest and easiest to use as very basic understanding of the software is needed to extract data. The GUI is quick to understand and can plot graphs within the program for immediate processed data that can also be extracted for further use. XFOIL is more complex to start with, once the software inputs are understood and method steps are prewritten for the users desired modelling conditions, the testing is relatively quick. To produce large amounts of data quickly is fairly accurate as stated previously I would suggest that JavaFoil be the chosen software to use for MAV developers dependant on developers need for accuracy. If these tests were to be repeated the reliability of the results being exactly identical is extremely high as the programs do not have any variables that would alter this information, only input errors could alter the results. X-FOIL has also been used to simulate a thin cambered reflex wing for an MAV (Pelletier and Muller 2000) and have been detailed good enough to model the effects of camber.

The downfall to the software is that they only model in 2D and that if the cross-sectional shape changes across the chord repetitive simulation would have to be completed to model the wing with accuracy due to the complexity of the wing shape and reflex change with chord length. The flight simulators for which the data would be used, ideally needs the inputs as 2D cross-sectional wing sections and so is fit for its purpose.

From performing the coefficient data to inputting data into the flight simulator calculations had to be completed including the required CG positioning and the stall speeds being calculated so not induced. This step was quite in-depth and lengthy and it shows a current gap in research and software available to develop MAV designs. This type of analysis can be seen in the Advanced Aircraft Analysis software created by DarCorportation (2009) for normal aircraft sizes and there is currently no software available specifically for MAV designs.

The results from JavaFoil were chosen to be used for the flight simulators to reduce the amount of testing that had to be carried out, because of this further testing could be performed to improve the validity of the coefficient data findings. More research could also be included into the production of coefficient data software that directly inputs into flight simulation software such as Digital Datcom of the entire aircraft design for FlightGear.

M. Flight Simulation Models and Software Analysis

When looking at the flight simulators from an MAV developers view point the simulators have to be flexible, easy to use and have enough detail to accurately simulate at this micro scale. The following discussion will look into each method step for simulating a design and how good it is and what improvements could be made. Merlin flight simulators come fully loaded with the software program and the Cessna aircraft model to begin your design. X-Plane and Flight Gear have to be downloaded and editing software including JSBSim these take more time but do not cost money as unlike Merlin. To create a model only an airfoil file and model file must be created unlike FlightGear JSBSim needs several different files which can mean more mistakes and more files that need to be managed.

The programming of the MAV model was taken from existing working models and altered by hand in available tools such as Notepadd++ or equivalent GUI editors to help identify correct methods of use however underlying problems can be caused by this method. Using X-Plane it simple to place the components in the required location as a visual output was created. This was particularly useful when placing the aileron and elevator position on the wing; however the depth of these control surfaces could not be altered. The automatic visual representation of the model is used for the graphical output within the simulation and cuts programming time compared to FlightGear or Merlin. Having a flight simulator that encompasses the visual representation of CAD software and technical ability to compute CFD modelling like XFOIL and JavaFoil would be ideal but currently none of the tested simulators have this capability. Digital DATCOM has a CAD type format and could be used to give a visual representation to the numerical values that were used to programme the FlightGear simulation model.

When editing the model the coefficient data input method is a look up table with AoA against coefficient's this is common between all three simulators but the detail is flexible with Merlin and FlightGear but set with X-Plane needing large amounts data inputs which increases the detail but also the computing power needed. When editing numerical values it is easy for Merlin and FlightGear as it is manually typed which is preferred over the scroll toggle buttons that are seen with X-Plane which slightly increases the time for programming. All the simulators can include the programmed aircraft's visual image to overlay so that it can be viewed by the user in flight and the range of formats is large for FlightGear and Merlin however DXF is suggested. X-Plane is different as it creates its own image from your input data and so programming time is reduced as no image file has to be created by the user. This feature is highly desirable and highly useful to spot errors in the programmed model regarding its shape.

When modelling the wing shape it is difficult to get the accuracy in both Merlin and FlightGear, where as X-Plane excels and can model 10 panel details of a horizontal surface which is now possible with Merlin's upgraded Excalibur II software. Inputting the engine and propeller specifications is limited in Merlin and FlightGear but X-Plane has the more complex and detail to simulate a propeller and also rotary aircraft. The new Merlin upgrade can simulate a rotor blade with more detail but still has limited breakdown of the inputs that it can use. In FlightGear it has been possible to simulate a rotary aircraft but the details are of military interest and cannot be published however it again is possible as long as the user spends time to input and program data using correct equations and available libraries.

Merlin model editing is simple and the data manipulation using the GUI is good due to the layout with limited data input variables. Conversely X-Plane's GUI is easier to use than editing manually like JSBSim but the vast amount of detail and different input variables is much larger and makes it harder to use the GUI. When creating your design model in the flight simulators a minimum amount of data is needed with Merlin this includes a fuselage, wing, undercarriage, engine, weight and CG. This seems relevant however some designs do not have a fuselage such as a blended wing body or an undercarriage for MAV's that are usually hand launched. Because of this these values were reduced so that they had limited affect on the model flight data. The FlightGear model did not have to have an undercarriage or fuselage which was required by Merlin and X-Plane.

To alter the loading condition in Merlin or FlightGear the model must be selected and the loaded conditions are then chosen and run. With X-Plane the conditions can be altered during flight using one of the chosen toggles to select the loading conditions, this method is quick like the Merlin GUI but the FlightGear process is extensive and time consuming. All flight simulators were started with a loading position of 55/70 knots at an altitude of 300ft for the CG location 0.02m (original scale) however this may not be the ideal location. If further tests were to be completed a range of altitude and CG locations should be tested in more detail recording the static margin. This may also help find the specific loading requirements for straight and level flight as the aircraft tends to climb with this current loading condition. This error could be created by the set incidence angle and may need to be altered and refined through further testing.

The scaling factor is a significant alteration that had to be made in the Merlin software and may affect the aircraft response if not computed correctly. It is also critical that all functions are scaled including Re as this cannot be scaled linearly. The weight should also be scaled proportionately using the square cube law. The major issue with modelling data in Merlin is the scale factor and that Merlin had to have an initial weight of 100kg or above to be modelled. This is not ideal for an MAV design developer and the reason for this restriction is due to the inertia calculation detail limitations. This should be resolved as soon as possible to reduce the risk of scale factoring errors and to encourage small scale aircraft development on this software. With X-Plane and FlightGear the MAV scale did not have to be changed and this should result in better accuracies however the inertia calculation accuracies is not specified and should be published. When validating the results from the simulators it should be noted that the model sizing and accuracy is dependant on the inertia calculations detail. Additional research should be performed to assess the scope of these computed variables. It should be noted that FlightGear's calculations are determined by the programmer and therefore there are no standardised detail but the detail of the calculation could round these input variables within the JSBSim Libraries.

The CFD results show that there should be an initial pitching motion due to the shape of the reflex camber with stabilising pressures after a short period of time. This visual time dependant results gives the developer greater detail and understanding of the design and if time and skills are available this process should be completed to identify problem areas associated to the flight dynamic analysis. Initially the pitch up motion and oscillations seen in all simulators was assumed to be caused by the separation bubble that occurs seen in the CFD simulation post processing results. This shows the bubble moving from the leading edge along the underside of the wing to the trailing edge. This is extremely interesting and as it could be perceived as highly accurate modelling however when looking deeper into the results the undercarriage and initial thrust increase could have also caused this initial pitch oscillation. This is due to the simulation problem when loading an aircraft into the air an immediate undercarriage retraction takes place. This movement is assumed the cause for the pitch input and oscillation rather than the aerodynamic behaviour with sudden air speed changes. The initial thrust increase is also unknown; it could be a simulation error or a resultant effect of the undercarriage retraction. The overall reaction shows an oscillation in pitch altitude and airspeed that is unwanted during flight. Due to the small inputs needed to alter the aircraft response this initial input should be removed. On a positive perspective the undercarriage deflection could be used to simulate the separation bubble moving underneath the wing to replicate hand launching but would not be correct for all aircraft being modelled in this equipment due to size and shape differences.

To overcome this flight simulation loading problem the aircraft could be loaded on the ground and then flown to the desired flight testing conditions. To be able to accomplish this the flight simulators need to have undercarriages even if the aircraft design would not require one when manufactured. This does involve more time developing components that are not needed for the aircraft design. Undercarriage designs were attempted and thrust applied when loaded on the ground; however the aircraft oscillated in pitch profusely and would not unstick from the runway. This is likely to be input errors in the undercarriage design programming and would need further attention for future analysis. By using this method it would then still leave the issue with raising the undercarriage and potentially having the same pitch oscillations occur. An alternative idea would be to reduce the drag to zero and the sizing to zero or as minimal as possible and to try loading the aircraft in the air to look for any pitch response. The transient time could also be reduced or extended to look for effects. A feedback system could be used to change $M\alpha$ or Mq within the aircraft model but would not be ideal as this would affect the pitch response for elevator deflection as well as undercarriage response.

The Merlin output from the undercarriage deflection and the thrust increase leads to an oscillation or the inverting of the aircraft with CG location 0.02m. When the aircraft inverts the oscillation is lost by the aircraft rotation and increasing angle of attack and loss of lift. When moving the CG location toward the LE producing a larger static margin the pitching movement reduces and becomes more stable as the inherent oscillation becomes smaller which is to be expected. The aircraft is however stable in pitch at 0.02m after the initial pitch rotation occurs, but it is not when the CG location is located further back and large instabilities are found these are again typical with CG margin changes. From loading the aircraft in the range of CG locations an ideal stick fixed neutral position was found between 0.155m and 0.173m. This was similar to that expected from the calculations seen previous at 0.02m. Further tests are needed to confirm that the location was correct as smaller increments can be used and oscillations at these points are still seen. The effect involving the wing increasing in pitch until it is fully inverted where it continues to fly in an inverted stable manor could be an effect of the double camber being a different ratio when inverted to 3%, 5% camber. Further testing should be performed into this camber ratio to find the ideal CG location as the properties will be different as the moments from the cambers will be different due to the area acting as a tailplane will be much larger and higher camber percentage.

Loading the FlightGear model at an altitude of 300ft and 40knots showed that the aircraft increased in speed toward 70knots to maintain a stable flight speed. When altering the loading flight speed the aircraft would still tend increase in speed at the start of the flight. This is a very similar affect to that seen in the Merlin simulations and shows that the initial increase in speed could be due to an alternate reason than that of the undercarriage retraction as no undercarriage was simulated in this model. This increase in speed is more likely to be a simulation error when loading a model in the air as the setting angle is high and the elevator may have to be used to trim the aircraft into a lower angle of pitch angle upon loading. Setting an elevator trim tab position can be done in both the Merlin and FlightGear models and should be tried to resolve the velocity inputs that affect the pitch and altitude response. The altitude and speed oscillations identify that there is a phugoid motion occurring during flight. The cause of the motion is normally excited by pilot control surface inputs.

The overall flight pattern for the stick fixed testing in FlightGear showed that the aircraft initial speed affects the pitch and produces an oscillation and also affects the altitude climb rate which can also be explained as a phugoid motion. Performing a velocity step input showed that the altitude climb rate is affected exciting the oscillatory motion but naturally dampens over a long period identifying the phugoid. It can also be noted that the input velocity decreases the pitch oscillations. The input velocity test should be repeated so that more of the oscillation is recorded so that the correct PID controller can be calculated and analysed to be implemented into the flight simulator to control this input if needed. Performing the pitch step input the pitch response is excited as the carrier wave and does not seem to affect the flight speed and climb rate. Both these tests show that the oscillations could be causes of the undercarriage retraction and speed changes. These tests also identify that the aircraft is dynamically stable when altering speed however has neutral dynamic stability in pitch as there is a continuous oscillation that does not dampen with time. This identifies that the pitch changes are the major cause for the neutral dynamic stability effects seen with this model identifying the need for further development with the CG positioning and tuning locating the CG forward towards the LE as seen improves the response in Merlin. Setting angle and undercarriage loading also need to be researched further.

There were no loading speed errors and when the model was initiated in X-plane the speed would only be relevant to the particular joystick command input. The thrust conversely remained at zero on initiation and increased over the testing time, normally 1.5s to a thrust relevant to the flight conditions due to loss of altitude. Oscillations occurred within the thrust output during the X-Plane results as seen in the other simulators models. The undercarriage was simulated in this model and was not retracted to avoid unnecessary oscillations, however they were still present. This now leaves the possibility that the velocity is the main contributing factor specifically due to the engine design inputs. With the current conditions during flight the aircraft is susceptible to large dynamic affects with small input changes which are typical of MAV's.

The lateral stability of the aircraft can be assumed stable in roll if there is no engine torque moment seen in the Merlin simulation results. Conversely X-Plane and FlightGear show instabilities in roll with initial loading from these extreme differences in simulation the error could reside in the input of the engine details as all wing designs are reflected in the other plane to stop differences in wing shape or size that could induce roll. This project was focused on the longitudinal dynamics of this specific MAV but highlighted the importance of assessment of both longitudinal and lateral testing when designing MAV's. Lateral modes that should be tested dependant on aircraft control surface designs should include roll subsidence, spiral mode and dutch roll mode. Ailerons were designed in X-Plane to control the roll seen in this simulation with no prevail as it is not the original source for the roll input that can assumed to be caused by the engine design. Due to the more complex input details needed in these two flight simulators this is likely to be the source for the error and with further engine design developments it is likely that the rolling motion could be resolved. It is clear that the roll instabilities are evident but since the detail of the Merlin simulation data is minimal for engine inputs this could be the reason for the dissimilarity between the models. The Merlin model is not as accurate due to the limited input variable but it is quick, easy to use however recent developments may have overcome this issue with increased inputs and more testing should be taken to verify this assumption and look at the new complexity effects on programming time (Merlin, 2011). To ultimately reduce or eliminated the roll performance the autopilot features could be used but this could only be created after all design features were corrected. Due to the vast number of inputs that X-Plane has the roll instability could be a result from only one small incorrect programming, because of this exact problem X-Plane could be deemed highly accurate but highly impractical to a new user or someone that wants to produce data quickly and effectively. Due to the immediate roll characteristic when loading the aircraft the longitudinal tests could not be performed as the elevator input had no effect on the outputted results in X-Plane. The velocity input did have an effect but due to the rolling motion and lack of lift the test was decided to be too inaccurate to perform. Due to X-Plane having no vertical wind modelling like the previous simulators the wind gust modelling could not be performed. This is a feature that should be incorporated into these flight simulators and would make the environment more accurate to that of the natural environment.

As noted previously tailplane developments could be completed with this type of simulation software and the choice of elevator, ailerons or elevons could be designed to help control the aircraft in flight. Validation of the control surface could be made using XFoil or JavaFoil creating a flapped section at the specific chord ratio. If an elevator trim is used in XFoil it should be noted that the trim tab output for the ailerons was highly uneven as the roll reaction changed when reloading the aircraft in flight. This error should be researched further as it may be due to the detail needed for this model is not possible or the aircraft may have unstable roll properties due to the wing tip vortices or there may be a problem with the current loaded prop and motor model. This unstable roll will affect the results as the aircraft will reduce the generation of lift whilst rotating into the inverted position and this will affect the pitch rate and altitude climb rate.

The aircraft climb rate is reasonably quick in the Merlin and X-Plane models despite the aircraft not being in the specific stable flight condition. Because the stable flight condition was not met and the oscillations created from the undercarriage retraction the stick free neutral position test and the longitudinal stability tests were not performed. This was due to the errors within the model creating effects that would result in incorrect findings. Supplementary research could be extended to overcome these problems to complete these tests. Using flight simulation software limits the user to specific output variables for analysis. Using joystick commands and recorded stick position can be used for stick force calculations however this is a limiting factor dependant on the hardware available. Using force feedback and complex hardware systems can allow for accurate data but the hardware must be similar or the same as that is being used during actual aircraft flight as human factors may affect results. Wind gust tests would not have been possible to perform as only lateral gusts or turbulence are simulated. This is a limiting factor when testing pitch response as pitch testing is then dependant on control surface inputs that are dependant on there design. The turbulence setting could not be used as the random gust response could not be recorded thorough outputs available to the user. The design flaw when testing that occurs across all three simulators is that wind gusts cannot be modelled vertically with a speed control. This should be developed so that longitudinal testing can be performed to simulate a natural environment and flight conditions. Turbulence can be tested but is on lateral nature and is also randomly generated and therefore cannot be controlled or used for testing.

Outputting data for analysis is possible for each simulator however the amount of values that can be outputted is limited and varies between simulators it is also a better reflection on how many computations are being calculated to simulate the model accurately. Merlin outputs the least amount of data in a txt file with 62 variables next is the JSBSim libraries with 161 variables this does include graphical output information and the most data is X-Plane with 133 areas with several data variables within each area which are all relevant to the aircraft model and do not include graphical output data. An issue that arose during testing found that the trim was not recorded on the HUD or instrument panel and had to be estimated in X-Plane. This should be repeated with the trim property being output along with CG location and trim location against a variety of altitudes to find the stable flight condition for all simulation software. The ideal CG location may be difficult to locate due to the very small changes in CG and the limiting factor of the simulated computed detail. The stick free neutral position tests were not performed in FlightGear as the stick input could not be output as a property and future research should go further into where this information is processed within the simulator so that it can be performed. The longitudinal stability tests should be repeated at a stable level flight condition to verify the results that were found and in the desired speed and altitude from further testing. The wind gust tests were not performed as for the same reasons stated for the Merlin simulators however the weather conditions that are stated do show the possibility to control the weather at varying altitude which is more detailed than Merlin.

The stability of the aircraft and the flight characteristics that have been found from the simulators are relatively similar but the results themselves should be validated by creating the design and flying it in the desired configurations. This has not been completed for this project but should be performed to verify the findings and if the simulators can model the aircraft response correctly. Errors could have occurred in modelling and they could also exist in the simulation programs so it is vital that a model is created and tested in real environmental conditions. The ideal MAV development for components and locations can be seen in appendix 1 for potential extensive research. The main issue that should be researched further is the desired motor and propeller, more calculations and further work should go into completing this section so that it is the same information for all three simulators for clarity of the model design. To validate the results found in these simulators other models should be created with this method and any other main design features that are not explained should be added to this method. Stall speeds could not be tested to find the aircraft limits as Merlin failed to load at this particular stall speed for this MAV and consequently the other models had to be loaded at similar testing conditions. The computational finding shows that the aircraft needs large damping in both longitudinal and lateral directions to make the aircraft controllable in flight. The pitch oscillations was to be expected and CG alteration can be made to resolve this however the extreme roll rate is much larger than expected and could mean that a redesign of the wing tips should be performed to help with this effect.

The ideal CG location for X-Plane was 0.019m or less which is highly similar to that seen across all simulators and calculations performed as this was the furthest forward CG location. If tests are repeated specific locations should be set and performed in all simulation software to allow for better comparative analysis. At this location the pitch became positive the oscillations in thrust were reduced, the roll rate was reduced and overall it had the highest lift to drag ratio. However more tests should be produced moving the CG forward to improve the dynamic effects. The only downfall to this testing was the loss of altitude at a fast rate across all CG locations owing to the possibility of incorrect engine input design. This is an effect of the incorrect engine and propeller settings for this particular model. What was also noted was that when moving the propeller and nacelle into an attachment position with the wing and undercarriage could severely alter the expected propeller speed. These slight movements could have affected the results and the model could have the correct engine and propeller in place so this should also be checked upon repeated research.

The ideal CG location in Merlin is 0.15m or less and FlightGear is seen at 0.01m as it pitches up and climbs in altitude however it still has a large pitch oscillation, but this should be removed with further work locating the CG further forward. This is highly similar to the Merlin model and the pervious calculations performed. This oscillation should be brought to the main attention regarding the flight characteristic that could be controlled as it could be compared to a swimming motion seen in natural animals such as penguins, dolphins and manta rays, further comparison on this type of flight characteristic should be performed. When analysing the MAV design, similarities arose to the Manta Ray as it has a similar body shape without the flapping wing tips. This animal has a high aspect ratio body shape with a low travelling speed that should also be seen in this design. The camber seen due to the aircraft being tailless is also seen with the mantra ray but is moveable to control the pitch. To help with the control aspect of the design the movement of the tail on the mantra ray should be studied. Having a slightly larger wing span like the Manta Ray means that the aileron controls can be moved outwards toward the wing tips for better roll stability. What makes the aircraft more complex is the need for the aircraft to be as light as possible to have the same lift to weight ratio. Research has previously been done into the Manta Ray movement and also created in into a helium filled aircraft by Festo (2010) which overcomes the lift to weight ratio however the principles for the shape and manoeuvrability are controllable. Changes to the MAV design could be to investigate the different types of propulsion methods so that they are light and provide enough thrust to overcome the drag and to avoid stall, ideally above 15m/s as predicted.

Overall the most difficult parts for the simulators were to model the camber shape, the vertical wind gusts and the flapping/morphing of a wing or component. These issues should be researched and applied to all three simulators that latter being the most difficult and complex to integrate into the software equations and simulation. If this were possible the developments of the MAV design seen in this model could be simulated and developed. The ultimate complexity of this task would be very large as the flight dynamic modelling would be different for a flapping wing. A simulator of this type has not been created and there is a need for it with MAV design however to simulate it accurately studies should be done into flapping wing flight dynamics and its laws. If this type of simulation was to be crated with one of these simulators it would be possible now to start programming with FlightGear due to its flexibility but again the usability would be poor unless a GUI was made.

Merlin could be seen as a good simulator but not necessarily for MAV's due to the scaling issues, it has a good GUI layout and is easy to use but has limited computed values and data that can be extracted for analysis. This simulator needs the most improvements if it were being used for MAV development but some issues that have been raised in this project have been correct by the new upgraded Excalibur II software. FlightGear is a highly flexible piece of software that lets the user manipulates the JSBSim Flight Dynamic Model libraries or can be used with other inputs to simulate FDM's with a visual output. The software is good but is only as good as the users understanding of flight dynamic calculations to programming the model and the user has to have basic programming knowledge to build a model. Because of its lack of conformity and not being very user friendly this model should undergo development of the existing JSBSim Commander GUI to interact with FlightGear correctly and this flight simulator would be better suited to the need of the MAV developer with a high level of skills in programming and aerodynamics. The calculating level of the program would be accurate enough for an MAV and being able to simulate in actual scale is a big bonus to this program however calculation detail should be investigated. X-Plane is a very detailed piece of flight simulator software with a good GUI structure to input results however it does not allow you to exclude certain data and the AirfoilMaker GUI needs development for double cambered airfoils. The detail that goes into calculating the response is highly impressive and the ability to test and produce data plots within the X-Plane software is extremely good. However this simulator may have over complicated itself and the layout of all the content on the GUI may need some improvement. Because this model is highly detailed and is relatively users friendly and can simulate at small scales this software is the most suitable for an MAV developer, the detail of the mass and scale could be increases if there were any negative comment that had to be made and the ability to model a wing only. Ranking the simulators in order of usability, accuracy and meeting the MAV developer's needs would be X-Plane, FlightGear and then Merlin.

VI. Conclusion

Hopefully this project it has covered for a new user how to run load and perform tests and how to critique them for modelling accuracy for an MAV fixed wing design. It should also have analysed an MAV model design with double camber and the flight characteristics of the design if built and flown. It was found that the three flight simulators had different positive and negative factors to simulate this type of model these were;

- The Merlin flight simulator was highly user friendly but less accurate and could not model the MAV scale and was less flexible with input variables having a GUI.
- FlightGear was highly flexible and could be used to program complex designs but was difficult to use and was only as accurate as the programmer's input details.
- X-Plane was highly accurate with a good user interface but complex to understand. The accuracy was high and the flexibility was low being a restrictive GUI so unusual designs could not be programmed correctly.

From this report the simulators were deemed possible to simulate the MAV flight characteristics but need improvements to be performed to increase the accuracy, FlightGear needs an experienced FDM programmer, Merlin needed to simulate the scale correctly but X-Plane had little simulation errors but could be more flexible with the GUI programming. All three simulators need improvements to their software if they are to be used for MAV development such as being able to model vertical wind gusts, camber and flapping/morphing wing designs with possibilities to be developed in FlightGear with the JSBSim FDM libraries.

The most user friendly software to an MAV design developer was X-Plane because of the accuracy and ease of use however it still had some problems that should be resolved. The MAV design shown in the project was unstable in roll due to engine input errors and could not be verified. It was also prone to pitch oscillations presenting a phugoid because of this further CG movement need to be computed and then a control feedback should be used to make the aircraft stable when needed. Work should be carried out by creating the actual aircraft to scale and testing it and making a comparison to validate the findings in the simulation software.

N. Future Work

The initial model fault spotted whilst modelling in JavaFoil at the leading edge should be altered and the simulation procedure should be repeated and altered for the flight simulator software. XFOIL data should be used in the flight simulators to compare the differences to the flight characteristics and dynamics to do this the pitching moments should be taken about the aerodynamic centre and not the TE. The removal of errors found when simulating the MAV design that is simulated in this paper should be completed. This includes the engine and propeller requirements to be analysed and found in more detail and be the same for each simulator to make a fair comparison. The propulsion system could also be scrutinised and developed as it was chosen by default and not researched. The testing of the model for the CG location should be more detailed as the MAV is of a very small scale to that of an aircraft and the ideal altitude and speed should be assessed in more detail. The testing of control feedback loops to improve the stability of the MAV design could be performed in the simulators. Repeating the testing conditions at lower flight speeds than those seen in the flight simulators should be carried out to look at the correct ideal loading speed and minimum flight speeds.

Other MAV models that have known flight characteristics and flight data should be modelled in the simulators to improve the validity of the findings, this includes other model configurations. The development of the MAV design seen in this project should be investigated further looking at addressing the current roll and pitch instabilities and looking to nature such as the manta ray for ideas could help. Software improvement should be made such as developing an easy to use GUI and creating flexibility amongst the software for MAV designs to be able to simulate movable wing. The niche is also there to incorporate all those good features of the three designs into an MAV design development tool such as the visual representation the usability of the GUI the detail of the calculation. When outputting it should provide the coefficient data of each component in a txt file with a data image file. One feature that could be added would be that it would have two settings, easy and complex for the basic model designer and the analytical stability model designer to improve the usability of the software for the user's needs.

Appendix

O. Appendix 1 – Desired MAV Components

Table 19 Component Location

Item	Mass (g)	Aerodynamic Centre	Source	Information
Airframe	5	-0.5		
Video Camera	1		KX-1 Micro colour CMOS camera (http://www.rangevideo.com/index.php?main_page=product_info&products_id=212)	Colour Camera (9.5mm x 9.5mmx 12mm) 75mA, DC: 3.3V-6V
Brushless flat DC Mircomotor	1.1	0	Faulhaber (http://www.faulhaber.com/uploadpk/EN_1202_BH_DFF.pdf)	Power =0.652W $\eta = 51\%$ Voltage = 4
GearBox			Parkzone (http://www.wonderlandmodels.com/products/parkzone-vapor-gearbox-without-motor/)	Parkzone Vapor Gearbox
Transmitter	7		Parkzone (only included in the full aircraft kit)	Radio: 3-channel 2.4GHz w/Spektrum DSM2 technology (included)
Power – Battery			Parkzone (http://www.wonderlandmodels.com/products/parkzone-37v-70mah-lipo-battery/)	*PKZ3001 70 mAh 1 cell 3.7V Li-Po Battery*
Propeller & Spinner	1	0	Parkzone(http://www.wonderlandmodels.com/products/parkzone-vapor-propeller-spinner/)	*PKZ3302 Vapor Propeller with Spinner*

P. Appendix 2 – Simulation Models

Available on request also found attached to hard copy in the format of a disk.

Q. Appendix 3 – Flight Simulation Analysis Proforma

Criteria	Merlin	Mark	FlightGear	Mark	X-Plane	Mark
1.Input method						
Coefficient Data Range	Any range/detail, good if limited data available	10	Any range/detail, good if limited data available	10	Good for accuracy, full 360 degrees, specific 1 degree increments & 0.1 degree increments (-20 to 20 degrees)	9
Method reading airfoil data	AOA and coefficients look up table file	10	AOA and coefficients look up table	9	Highly detailed file- edit in Notepad++ to be able to use with low Reynolds number	8
Inputting values	Each section is clear, type in entry, no visual help.	7	Ok, difficult to master if don't have previous programming knowledge, highly flexible, no visual help.	5	scroll tabs annoying, each section is clear, visual guidance highly useful	8
Image Files	DXF	5	VRML1, AC3D, DXF, MDL and more	8	Own shape using Plane-Maker (can overlay)	10
Method to use Autopilot	Using GUI interface	9	Extra .xml file	7	Should be inputted into a flight deck and then used in flight	8
Method for Damping	Pitch, Roll and aw damping within Excalibur software as a function of 1.0	8	To be input into an autopilot file with gain and filer factoring.	8	Using PlaneMaker via toolbar toggle selection of set inputs	8
Compatibility and Installation	Preinstalled on Windows	10	Install on; Windows, Linux, and Macintosh.	9	Install on; Windows, Linux, and Macintosh.	9
Flapping/Morphing wing	No	0	No	0	No	0
Rotary wing	yes (New 2011)	6	yes (one military model that cannot be edited or viewed but is possible)	10	yes	10

2. Simulation Editing						
Manipulating Data	easy to change values and easy to find	8	easy to change values but had to search through to find the correct value	7	easy to change individual values and easy to search for it	8
Values that have to be input to be flown.	Fuselage, wing, undercarriage, engine, weight and CG.	7	Wing, engine, propeller, weight and CG.	8	Wing, undercarriage, engine, propeller, weight and CG.	8
Does the model need to be increased in scale?	Yes, needs to be over 100kg	5	No	10	No	10
3. Testing						
Loading model situation	In air at minimum of 50knots at any location above the ground or on the ground.	5	On ground or any location and speed	10	On ground or any location and speed	10
Tested in crosswinds	Yes - Controllable on upload/during (Environment) - direction(deg) and speed (knots)	8	Yes - Controllable on upload (Advanced options/Weather) - direction(deg) and speed (knots)	5	Yes - Controllable during (Environment/weather) - direction(deg) and speed (knots) (3 layers of altitude)	10
4.Outputting						
Format	.txt file	5	.csv standard but can be saved to any specified file or location	7	Data can be analysed in the software or exported the Data.txt file	10
Output Data	62 outputs	5	161 outputs (some none relevant)	7	133 areas more within each area, too much as can only select 5 areas	9
Overall Analysis & Total		**99**		**113**		**127**

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